MINUTES
OF THE TWENTY-FIFTH
EXPLOSIVES SAFETY SEMINAR

VOLUME I

Anaheim Hilton Hotel
Anaheim, California
18-20 August 1992

Sponsored By
Department of Defense Explosives Safety Board
Alexandria, Virginia

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PREFACE

This Seminar is held as a medium by which there may be a free exchange of information regarding explosives safety. With this idea in mind, these minutes are being provided for your information. The presentations made at this Seminar do not imply indorsement of the ideas, accuracy of facts presented, or any product, by either the Department of Defense Explosives Safety Board or the Department of Defense.

DAVID K. WALLACE
Captain, USN
Chairman

TWENTY-FIFTH DDESB EXPLOSIVES SAFETY SEMINAR

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TWENTY-FIFTH DDESB EXPLOSIVES SAFETY SEMINAR

OPENING REMARKS AND WELCOMING ADDRESS

by

Captain David K. Wallace
U.S. Navy
Chairman,
Department of Defense Explosives Safety Board

Thank you Paul. And welcome ladies and gentlemen.

Under this roof we've gathered explosives experts from government and industry from all over the globe. Scattered among you are dignitaries from many different disciplines. I'm not going to risk slighting any one of you by trying to call you out by name. Suffice to say that we are honored by your attendance, whatever level of contribution you make to the noble work of explosives safety.

Upon this dais we've assembled speakers from the highest levels of involvement in the entwined triangle of mission, resources, and risk management. I look forward, as I know you do, to hearing from Rear Admiral Bondi, Mr. Tom Baca, and our Keynote Speaker, Mr. Colin McMillan. Thus, we begin the general session of the 25th Explosives Safety Seminar.

Our first speaker is Rear Admiral Peter A. Bondi, Fleet Supply Officer for the U.S. Pacific Fleet. His fleet and headquarters experience has uniquely prepared him for the responsibility of orchestrating a logistical symphony of meeting the fleet demand for bullets, beans, and black oil.

I first met the admiral during the 1992 DDESB survey of the Pacific Basin. I came away from that meeting convinced of the admiral's intense interest in minimizing the risks associated with the movement of explosives in the Pacific Basin.

I'm grateful that he accepted our invitation to speak and I wish you would note that in the Pacific, explosives safety joins with logistics in the hulls of our Pacific Fleet ships, on the wharves of our commercial and military piers, and in the naval weapons stations and naval magazines throughout the Pacific. Our first speaker is intimately familiar with the explosives environment and the risks it holds.

Ladies and gentlemen, it is my distinct honor to present Rear Admiral Peter A. Bondi.

INTRODUCTORY SPEECH
25TH EXPLOSIVES SAFETY SEMINAR
BY

Mr. Thomas Baca
Deputy Assistant Secretary of Defense for Environment

SAFETY AND ENVIRONMENT

THE CHALLENGE SHARED

Thank you, Dave for the kind words, and I am very pleased to be with you at this excellent forum. It's impressive.

The Honorable Colin McMillan , Rear Admiral Bondi, honored guests, ladies and gentlemen. The theme I have for you today is a simple-one, the common bond between Safety and Environment, the shared challenge. Both Safety and Environment find their roots in human experiences.

I'll trace the parallels for you briefly:

One of the early pioneers in the United States who expressed concern about the environment was Henry David Thoreau.

In 1845, he retired to Walden to form his philosophy -- one that
he could not separate from the peace and beauty of his surroundings.

At about this same time in Europe the explosives industry was making milestones: Nitroglycerin and nitrocotton were prepared for the first time for use in propellants and dynamite.

Alexis Du Pont, one of the founders of the black power industry in the United States, died in a plant explosion while attempting to save his friends.

In 1874 George Marsh Published "The Earth as Modified by Human Action," A thesis of how we impact the environment. During these years Alfred Nobel constructed nitroglycerin plants in Sweden and lost his brother to an accidental explosion. In 1875 an explosion in Birmingham, England killed 53 people. Parliament passed the Explosives Act, placing tighter controls over the Explosives Industry in the United Kingdom.

At about the same time in the United States, Yellowstone and Yosemite were dedicated as National Parks, the Forest

Reserve Act cleared the way for additional forests and parks. The Sierra Club was founded by John Muir, and Cornell University offered the first college program in Forestry.

The World of Explosives saw the perfection of solid and liquid propellants by Germany, France and England; the development of dynamite and a host of Military explosives were developed, which are still in use today. In New York Harbor, engineers set off 99,000 pounds of dynamite and potassium chlorate to clear a navigation menace; the largest amount of explosives ever used at one time. But, all explosives were not as friendly. On July 10, 1926 a series of blasts at Lake Denmark killed 19 people and injured 38. The public demanded congressional action. Following a complete investigation. The 70th Congress established the Organization we now know as The DoD Explosives Safety Board.

Disasters also drove the Environmental Movement. A few years after the Lake Denmark Explosion, the greatest Drought in U.S. History fostered The Grazing Act, Soil Conservation, Wilderness Societies, Flood Prevention, Fish and Wildlife Service -- finally establishing The U.S. Bureau of Land Management itself.

In 1944 the United States was rocked by an explosion at port Chicago, California, perhaps the most devastating in DoD History, killing and injuring over 600 people. This tragic incident provided many Quantity Distance (Q-D) principals still written in the DoD Safety Standard today.

In 1948 in Donora, Pennsylvania, 20 people were killed and 14,000 were sickened by an air pollution incident. In 1953 the public learned that radioactive fallout from bomb tests was found in the thyroid glands of children, living in Utah. Eighty people were killed by air pollution during a four day Atmospheric Inversion.

In New York in 1966. An oil spill in Santa Barbara focused national attention upon the growing specter of polluted Air and Water. The Environmental Protection Agency was established in 1970, the same year that the Occupational Safety and Health Act was passed.

The Explosives Community was shocked in the 1970s when buried munitions appeared in a Formerly Used Defense Site. Munitions washed down rivers and creeks during the times of flooding, and were found by children at play. These incidents forged a major link in the merger of the interests of Safety and Environmental Communities. In 1975 the DDESB enacted rules for the Decontamination process for clearing DoD lands before

leasing them to the public. The Board recently modified this rule to harmonize with the Formerly Used Defense Sites and Base Realignment and Closure Programs which will be discussed by Mr. McMillan in his Keynote address.

There are many more examples. Titles alone will tell the story. Bophal, Love Canal, Three Mile Island, Chernobyl, Times Beach, Missouri, The Exxon/Valdez... Congress reacted. People around the world reacted. They reacted throughout the years to the devastating explosions that forged the development of our Safety Program. They are shocked and alarmed over the tremendous challenges now threatening our Environment. The Safety Professional must confront the potential explosive disasters as an Environmental threat.

Many of the environmental health and protection issues associated with the modern Environment of our nation and the world continue to become increasingly complex, and some may be intractable.

The causes of Environmental Degradation are manifold. Environmental problems impacting human health and safety are interwoven. The ecological maxim that "everything is connected to everything else" becomes more apparent each day.

Solutions to our Environmental ills are as complex as the cause, and opinions as to solutions are as varied as opinions regarding their nature and causes.

The DoD defines Environment in a very broad way: The air, water, land, cultural resources and all organisms living therein, and the interrelationships that exist among those. In the Department of Defense, Environmental issues encompass restoration, compliance, natural and cultural resources stewardship, pollution prevention, occupational health, fire protection, pest management, and <u>safety activities</u>.

The Department of Defense has pledged to be the Federal Agency Leader in Environmental Protection. Mr. McMillan will present the scope of the war we plan to wage in DoD's voluntary Program to lead the US in protection of Human & Natural Resources.

I want to motivate you, The Safety Professional, in the protection of people and resources from explosive accidents.

We need you scientific talent to define and reduce the risks into a manageable formula. We need engineers to implement innovative & creative technology. We need the fine tuned program you developed for Safety management to extend into the management of our Planetary Resources. We need to

extend your dedication to yet another worthwhile task, protection of the Earth, the Water, the very air we breathe for ourselves and future generations.

Ladies and Gentlemen, as you present papers at this Seminar, as you seek to understand the explosives technology essential to your duties, as you continue to excel in the fine work of accident prevention, remember my cordial invitation: That you expand your thinking to define safety in its broadest sense, as a part of Environment.

Thank You

Keynote Address of Opening Ceremonies
at the 25th Safety Seminar
By
Colin McMillan
Assistant Secretary of Defense for
Production and Logistics

Tom, thanks for that kind introduction. I am delighted to be with you today, I'm certainly going to take off from where Tom started. He just summarized over a century of change in the explosives business. And I want to talk to you about change.

There's been incredible change in the world since I came to Washington, since George Bush became President. And I want to talk about those changes. The world changes, changes to the Department of Defense, the changes in DoD's approach to the environment, and finally how all these changes will affect the Explosives Safety community.

Lets look at world changes for a minute. In the last two and a half years, there's no Berlin Wall, there's no Warsaw Pact, there's no Soviet Union, the Russian Tri-Color instead of the hammer and sickle flies over the Kremlin. It is against the law to be a communist in Russia, and legal in the United States. That's change.

Likely conflicts continue. There're now regional, those conflicts we may face in the future, most likely regional, not global. Such as Grenada, Panama and Kuwait.

The changes that pattern the world are directly affecting the Department of Defense. America no longer needs a military size on cold war threats. And we've made significant changes there. Everyone whose associated with Department of Defense knows that very well.

From 1985 to 1997 we will reduce the DoD budget by a third. We're reducing active duty military by half a million, civilians by nearly a quarter of a million, and active reservists by another quarter of a million. We're reducing the size of the Department of Defense by a million people. We cancelled nearly a hundred weapon systems. We're closing bases in the United States, and bringing home depot maintenance workload transit from Germany.

We're involved, and have been for sometime, in Defense Management Review, which has lead to massive changes in the way we're doing business in the Pentagon and has lead to significant savings.

We're changing the way we do business in the environment. There's a significant contrast between what we're doing in environmental compliance and cleanup, and what we're doing in the rest of the Department of Defense. While the Defense budget is going down, environmental compliance and cleanup budget is going up. In the President's State of the Union speech in January, he reaffirmed his commitment to the environment.

And we in the DoD have put our money where our mouth is. Our budget requests for this fiscal year coming up, fiscal year 93, is 3.7 billion dollars, for compliance cleanup, and 28% increase over the 1992 budget base, and its almost tripled, for what we were spending in 1990. It's a 450% increase in cleanup budget since 1985. On top of that this year, we are asking for another billion dollars, supplemental money for current fiscal year for compliance and cleanup. So we're coming down on one side and going up on the other.

Let me tell you some of the things that we are doing in the environmental area. The Defense Environmental Restoration Program is involved in cleaning up toxic waste. By the end of FY91 we identified over 17,000 potential sites, at 1800 installations as potential contaminated sites. Fortunately only 89 of these installations were on EPA's National Priority List. That's a big number, but we're delighted that we've gone through studies and found 204. But its a big number to cleanup, big dollar, large number of installations and sites. We estimate in cost 25 billion dollars to do that.

We're committed to environmental compliance. We planned to and we are actively engaged in the idea of complying with all applicable State and Federal laws and regulations. We are investing in hazard waste storage, treatment disposal facilities necessary to meet the Clean Air and Water Act requirements, involved in Endangered Species Management, histortical property preservation and so forth.

Department of Defense is a leader in Pollution prevention. Hazardous waste disposal is a prime example. The best way to take care of problems with our environment is to stop them before they start. As part of that commitment, we set the goals of reducing in five years, our hazardous waste disposal by 50%. Our goal is due at the end of this fiscal year. We've reached that goal at the end of FY91 by reducing hazardous waste disposal by almost 54%.

How are all the changes in the world and the Department of Defense affect explosive safety? Two primary ways. DoD downsizing drives virtually everything we're doing. And the environment touches everything you do and how you do it.

As I've discussed with you, we're closing bases, reducing personnel, eliminating weapon systems. These reductions have affected the safety community as much as any other segment of the Department of Defense. Obviously we have fewer guns, fewer people to shoot then we need smaller inventories of ammunition. Downsizing has resulted in a very large excess of conventional and chemical weapons. We used to average 24,000 tons of munitions awaiting disposal annually. We now have 200,000. Part of that has to do with the war, the war in Southwest Asia and part of it has to do with downsizing.

As we close military installations both in the United States and overseas, we have to remove ammunition, eliminate storage magazines, and clean up firing ranges and impact areas. We have to confront the challenge of moving and destroying aging munitions that may have rested untouched for decades. While destruction of munitions was once a side note, it's front page news both in Europe and the United States. DoD is spending hundreds of millions of dollars to safely destroy chemical and conventional weapons.

You will be tackling the tough new tasks resulting from the end of cold war with a new set of rules. The growing application and stringency the State and local laws and regulations will present a tremendous challenge. Such rules vary not only from state to state, but from county to county. And if you have a military installation that's in more than one county, you may have different rules for different parts of the base. As a matter of fact, in addition to that, you've got the air-quality areas. So you could have an air-quality district in two or three counties and you really have your job cut out for you. And I'm sure that you'll be pleased to hear this, those of you that are in Command situations, that under proposed new Federal Facilities Compliance Acts, states will be able to assess penalties for violations of their environmental rules. So you have a whole new set of rules.

But we can meet that challenge. It's clear as I go all over the United States and our bases, we got the talent to do it, so I am not worried about it. But it is a new dimension. And frankly I think what we've got to do, in State and local government is to convince them that we both got the same problems and we need to work together in solving them.

Formerly use defense sites are becoming a very real problem, as we continue to close bases. Old firing ranges contain explosives that are buried many feet down. Although we're committed to return these sites to clean status, words like "innocuous, pristine, or original condition," may not be appropriate. Rather, in cases where land cannot be rendered entirely safe, and there are those sites, that are not going to

be rendered totally safe. Specific instances, we are going to have to restrict the use of that land to positive activities, but activities like wildlife. In populated areas where the unexploded ordnance cannot be left in place, we're developing new approaches.

The challenges facing you in the Explosives Safety Community are as great as any in the Department of Defense. I know that the talent exists within the Explosives Safety Community, to solve these problems, to meet these challenges. With your abilities and energy, I have the absolute confidence that you can do the job.

Thank you

An Address to 25th Safety Seminar
By
Rear Admiral Peter A. Bondi, USN
Fleet Supply, CINCPACFLT

Good Morning, Ladies and Gentlemen

As I look out at this audience and see all this expertise, resident in the subject of Explosives Safety, I think about my own rather limited credentials in that regard.

I would like to, in the Field that we are addressing today, just talk a little bit about some of the evolutions that have taken place in the recent couple of years, in this area, and one of course is instantly reminded of Desert Storm. And I would like to talk about perhaps a little more in detail about the closure of Naval Magazine in Subic Bay. Which I will address in just a second. But both of these evolutions, I would suggest to you are unparalleled in the amount, complexity, and urgency of ordnance moved. And the successful accomplishment of both of them is a tribute to the logistics ordnance, logistics experts, many of them are here today.

To talk just a second about the Subic Bay, because some of you are not probably familiar with it. As you know the United States is obligated to be out of the Philippines and out of Subic Bay by the end of this year, and Ordnance plays a very vital part. As I stand here today with you the very last ship is being loaded in Subic Bay. By the end of this week, the last loading will be completed. We will have a complex, which comprised of over 5600 acres, having over 224 magazines and two ammunition wharves. We will have in 8 months moved over 42,000 tons of ammunition. We've moved it to places in Hawaii, and here in the mainland and California but also in locations like Jokosuka, Sasebo, Japan, Guam, and Chinhae, Korea. We have swept all the disposal ranges. We have completed all of the underwater searches and the ammunition, as I say by the end of this week, will have been moved, lock, stock and barrel without an explosive mishap or without one lost dud. That is a tremendous accomplishment by a number of very dedicated professionals. And it seems to me the lesson learned that evolution in Desert Storm, are that any program involving explosives safety must necessarily entail, in the Department of Defense, Joint Service discussion in cooperation. Communications that are absolutely critical to the success of the operation. And of course, one that all of you are familiar with, a necessary setting of standards, of periodically revalidating those standards and strenuously adhering to them. This will be a tremendous test for all of us. Particularly in

the constrained and restrained resources that we are going to go through. There are going to be temptations, to lower our standards. And it becomes critically important that we not fall victim to that temptation.

It seems to me that in any program of Explosive Safety, to be successful, must be comprised of five elements. Documentation, assessment, facility site survey, enforcement through explosive safety, inspections in education.

My role in the Pacific fleet is to preside over a good share of this, with regard to the ammunition security and safety. And my real role here today, is to assure you, that the United States Navy is completely supportive of the work that all of you are doing. We are dedicated, like the people in attendance at this Seminar, to safe operations throughout the world.

I want to extend on behalf of the Pacific Fleet and the US Navy our best wishes to all of you, all the attendees, and our wishes that the fruits of your labors this week, may result in even safer explosives safety operations.

Thank you very much.

THE ESTABLISHMENT OF A TRI-SERVICE AMMUNITION DEMILITARISATION FACILITY BY THE UK MINISTRY OF DEFENCE

Major Alan R Davis, Directorate of Land Service Ammunition,
Vauxhall Barracks, Didcot, UK.

Presented at the
DEPARTMENT OF DEFENSE EXPLOSIVES SAFETY SEMINAR
18 - 20 August 1992
Hilton Hotel, Anaheim, California.

ABSTRACT

The advent of more stringent environmental legislation and the loss of Crown Immunity from such legislation has forced the Ministry of Defence to adopt a 'Green' approach to the demilitarisation of ammunition surpluses.

As part of its strategy for the future, the Ministry of Defence (MOD) intends to establish a Tri Service Ammunition Demilitarisation Facility based on rotary kiln incineration technology. This presentation provides an insight into the proposed design of the facility.

INTRODUCTION

In the past, techniques for the demilitarisation of ammunition in UK were designed to meet three criteria: to be safe, efficient and as economic as possible. It is only in recent years that ecological considerations have impacted on established procedures sufficiently to force a new approach. UK is now in that transition period towards the introduction of demilitarisation techniques that are ENVIRONMENTALLY safe, efficient and cost effective. Today I will provide a brief overview of the reasons for change in UK and then describe our proposals for the development of a Tri-Service Ammunition Demilitarisation Facility (TADF).

This subject deals with the logistic disposal of ammunition, that is ammunition stocks which are be disposed of as part of the inventory management process. It does not relate to operational demolition techniques which of necessity give environmental considerations a low priority.

The term 'demilitarisation' is used in this paper to refer to disposal processes which destroy functional characteristics and prevent further use as an item of ammunition, rather than alternative disposal methods such as sale to a third party for operational or training use.

IMPETUS FOR CHANGE

For many years the UK has relied on a combination of sea dumping and open range demolition to dispose of ammunition and explosives. However, in the face of growing national and international awareness of ecological issues and in particular the environmental impact of industrial waste disposal processes we have re-assessed our attitudes to demilitarisation. The specific events which have affected UK are:

1. The progressive loss of traditional disposal resources.

2. Strengthening of environmental legislation and in particular the removal of Crown Exemption for the military.

LOSS OF TRADITIONAL DEMILITARISATION RESOURCES

Dumping at Sea. UK has traditionally relied upon sea dumping to dispose of the majority of it's surplus ammunition. Since 1972 strict controls have been imposed over the natures of ammunition dumped and the dump site itself. All ammunition and explosives have been dumped in a single deep sea site in the Atlantic at a depth of 4525 metres. UK is already committed to protocols under the OSLO Convention which prohibit the dumping of industrial waste (including ammunition and explosives) in the North Sea. From 1 January 1993 the OSLO Convention will be officially extended to encompass the European half of the Atlantic which includes MOD's dumping site. This imposes a clear deadline for the termination of deep sea dumping and requires that alternative methods of disposal are established.

Open Range Demolitions. There are very few truly isolated places in the UK and explosive limits on demolition ranges have been progressively reduced over recent years in response to complaints from the public over noise and ground shock. In many areas it is no longer economical to employ demolition techniques for logistic disposal tasks and there is a growing recognition that ranges are better employed in support of operational and training requirements. It is also recognised that environmental considerations will increasingly restrict the range of munitions which can be disposed, making it even more necessary that MOD develop other means of demilitarisation.

ENVIRONMENTAL LEGISLATION

The Environmental Protection Act (EPA), passed in November 1990, is a stronger and more enforceable piece of legislation than was previously in force.

Under the EPA, waste processes are required to meet Best Available Technique Not Entailing Excessive Cost (BATNEEC) and Best Practicable Environmental Option (BPEO) principles. Although guidance notes have not yet been issued, it is expected that the following air emission limits (based on EEC proposals) will apply to the burning of waste up to 1 tonne/hour:

Particulate matter	20 mg/m3
Sulphur Dioxide	50 mg/m3
Hydrogen Chloride	30 mg/m3
Hydrogen Fluoride	2 mg/m3
Carbon Monoxide	50 mg/m3
Oxides of nitrogen as NO2	650 mg/m3
Total free halogen's	5 mg/m3

Heavy Metals and their compounds (expressed as metals):

Cadmium & Thallium together	0.05 mg/m3
Mercury	0.05 mg/m3
Antimony,arsenic,lead,chromium, cobalt,copper,manganese,tin, nickel & vanadium together	0.5 mg/m3

Dioxins and Furans:

Maximum Toxic Equivalent Value(TEQ)	0.1 ng/m3

Odours:

No offensive smell o'tside premises.

Plume:

No visible plume within 5 minutes of start up.

MOD does not enjoy Crown Exemption from the EPA although operational training activities are necessarily exempted from noise and smoke provisions. This does not extend to range activities which are unconnected to operational requirements, such as logistic disposal of ammunition stocks. This imposes a clear requirement on MOD to ensure its procedures meet the provisions of the EPA.

MOD STUDY INTO DEMILITARISATION NEEDS

It was against this background that in 1989 the MOD conducted a detailed study into UK and overseas ammunition disposal techniques with the aim of identifying a cost effective and environmentally safe approach to demilitarisation.

FINDINGS

The study found that the MOD needed to demilitarize between 2000 and 5000 tonnes of ammunition each year and recommended that this be achieved using the following means:

1. Contract to industry for the demilitarisation of all large production runs or items representing specific hazards.

2. The establishment of a Tri Service Ammunition Demilitarisation Facility (TADF) designed to process ammunition which was not suited to contract disposal.

3. Open range demolition should continue to be used in a limited way for the disposal of some high explosive filled items by detonation and conventional propellants by burning.

Having provided some background into the reasons for change in UK I will now concentrate on the TADF for this is the project currently foremost in our minds.

DEVELOPMENT OF A TADF

CONCEPT

Although we intend to rely on industry for the majority of our demilitarisation requirements we believe that there will always be a need to process some munitions within the Service. In particular we want to establish the TADF to handle those incidental quantities that arise from stockpile surveillance activities and also items recovered by EOD operations throughout UK. We anticipate the annual throughput will range from 700 to 1700 tonnes.

In developing the TADF concept we were conscious of the need to meet the following broad requirements:

1. **A Wide Spectrum of Natures Handled.** The ammunition and explosives processed by the TADF will comprise small quantities of items from an extremely diverse range of different designs and fillings. Current service items will

cover almost the complete MOD inventory and EOD recoveries will span various countries of origin and may well go back a hundred years or more.

2. **To Function as an Ammunition Process Building.** To achieve operating economies, it is intended to locate the TADF in a major ammunition storage complex, within an Ammunition Process Area. The preparation and demilitarisation processes will be integrated , rather than being separated with the incineration process located in a remote demolition area. This requires that the complete TADF operates in accordance with explosives safety regulations for ammunition process lines.

Designing a facility to handle a wide range of natures invariably involves some compromise in the design and selection of the demilitarisation process. In the final analysis, it is very difficult to cover every possibility. After detailed study we concluded that rotary kiln incineration offered the most flexible approach and lowest technical risk for the TADF.

The range of items to be processed by the TADF are as follows:

1. Small Arms Ammunition.
2. Pyrotechnics, including smokes, dyes and CS compositions.
3. Grenades, fuzes, primers, and similar.
4. Carrier Shell.
5. HE filled munitions up to 600mm diameter and 1200mm long.
6. Cast Rocket Motors, up to 600mm diameter and 1200mm long.
7. Contaminated metal (EOD scrap).

We recognise that successful processing is highly dependent on effective preparation of munitions prior to incineration to ensue correct sizing and venting and on tight control of the feed and incineration phases. We are also aware that it will not be feasible to design the TADF to handle literally every munition in our inventory. There will be some munitions which require special processes and others where the throughput will not justify the investment to cater for them.

FUNCTIONAL LAYOUT OF THE TADF

The main functional areas of the TADF are shown at Diagram 1. It is our intention that these areas should be provided within one facility as this will afford the most efficient operation. Of course there will be a need to protect those process areas which are manned from an event in adjacent areas and this will require container traverses and some physical separation.

This facility will be constructed on a green field site within the Ammunition Processing Area of the Army's Central Ammunition Depot (CAD), Kineton, Warwickshire. This CAD is a modern facility with excellent infrastructure support to assist optimisation of TADF operating efficiency.

The functional areas of the TADF are largely self explanatory and similar to other processes which have been discussed in this forum before. I will therefore restrict myself to those aspects which I believe are of special interest.

IDENTIFICATION

Identification of items intended for processing is important in any demilitarisation facility, but especially so in the case of the TADF which will handle a wide range of items including EOD recoveries. For

this reason the TADF will incorporate X-Ray and facilities allowing the chemical analysis of fillings to ensure the positive identification where necessary.

PREPARATION AREA

The Preparation Area comprises three main process lines.

1. **Contaminated Metal.** This line will process EOD scrap which is normally received in post pallets. Where necessary it must be cut to size for feeding into the incinerator and/or mutilated to destroy military characteristics.

2. **Small Munitions.** This line will handle the majority of live items processed by the TADF. The initial work stations allow for unpacking and removal of inert components which should not be fed through the kiln. Where necessary munitions will be vented by punching or shearing to minimise the potential for transition to detonation in HE or high energy pyrotechnic fillings.

3. **Large HE Warheads and Cast Rocket Motors.** This line will incorporate a high pressure water jet cutting machine to expose fillings and size them to enable controlled incineration. Although water jet technology is now well demonstrated we do not believe that a process for handling explosive contaminated water has yet been proven. The development of a suitable machine therefore represents a real challenge to us.

Only one process line will operate at a time and at this stage we do not envisage mixed feeds. This is clearly feasible in theory and may be a later development. For example, where live items are fed at a rate below the capacity of the kiln, it would be possible to mix in contaminated scrap to achieve higher throughputs.

EMISSION CONTROL

The TADF will need pollution control equipment capable of handling the wide spectrum of munitions that we anticipate processing and ensuring that air emission limits specified under UK environmental regulations are not exceeded. At the moment we anticipate the pollution control equipment will have to comprise an afterburner, cooling system, scrubber, particulate removal process and dehumidifier.

Water treatment processes will also be required should the TADF incorporate a wet scrubber in pollution control, a high pressure abrasive waterjet machine in the Preparation area or a water deluge system to ensure process safety.

CONTROL SYSTEM

The TADF will incorporate a central computerised control system for the incinerator, pollution control equipment and automated preparation processes. This system will enable automated or manual control of operations and provide a separate safety loop to initiate progressive shut down should potentially dangerous situations develop.

We believe that this system will be essential to ensuring that transition to detonation does not occur when processing larger HE items as it will enable balancing of feed and fuel rates to maintain internal kiln temperatures within precise limits.

The control room will also be linked to automated processes in the Preparation and Incineration Areas by CCTV. In particular these will monitor sectioning of large HE filled items or cast rocket motors, the conveyor feed system, rotary kiln and discharge process.

IMPLEMENTATION PLAN

We are aiming to have the TADF built and commissioned by 1995. The feasibility phase of the TADF Project is now all but complete and we anticipate moving into the detailed design and construction phase in the near future.

Although the TADF will be built in an existing ammunition depot on MOD land it is still necessary to seek planning approval from local government authorities. This process has already commenced and is creating some local public interest. We anticipate planning approval early next year.

To reduce technical risk and development lead time, we will use existing technology and proven equipment where ever possible. For example, we intend to use the US DOD APE 1236 Rotary Kiln for incineration as it has a proven track record. The pollution abatement equipment on the APE 1236 does not meet our requirements and so will be developed separately.

CONCLUSION

We have been extremely fortunate in being able to draw on the experiences of the US DOD in developing the TADF project. There is no doubt that we would have otherwise spent many years in proving project feasibility and trialing the specific demilitarisation techniques before getting the TADF off the ground.

Despite this advantage we still face specific challenges to develop a facility able to cope with a wide spectrum of munitions in a cost effective way and also to meet the stringent emission control limits required by UK and EEC authorities. For this reason we feel the TADF will represent a positive move forward in the overall development of ammunition demilitarisation technology.

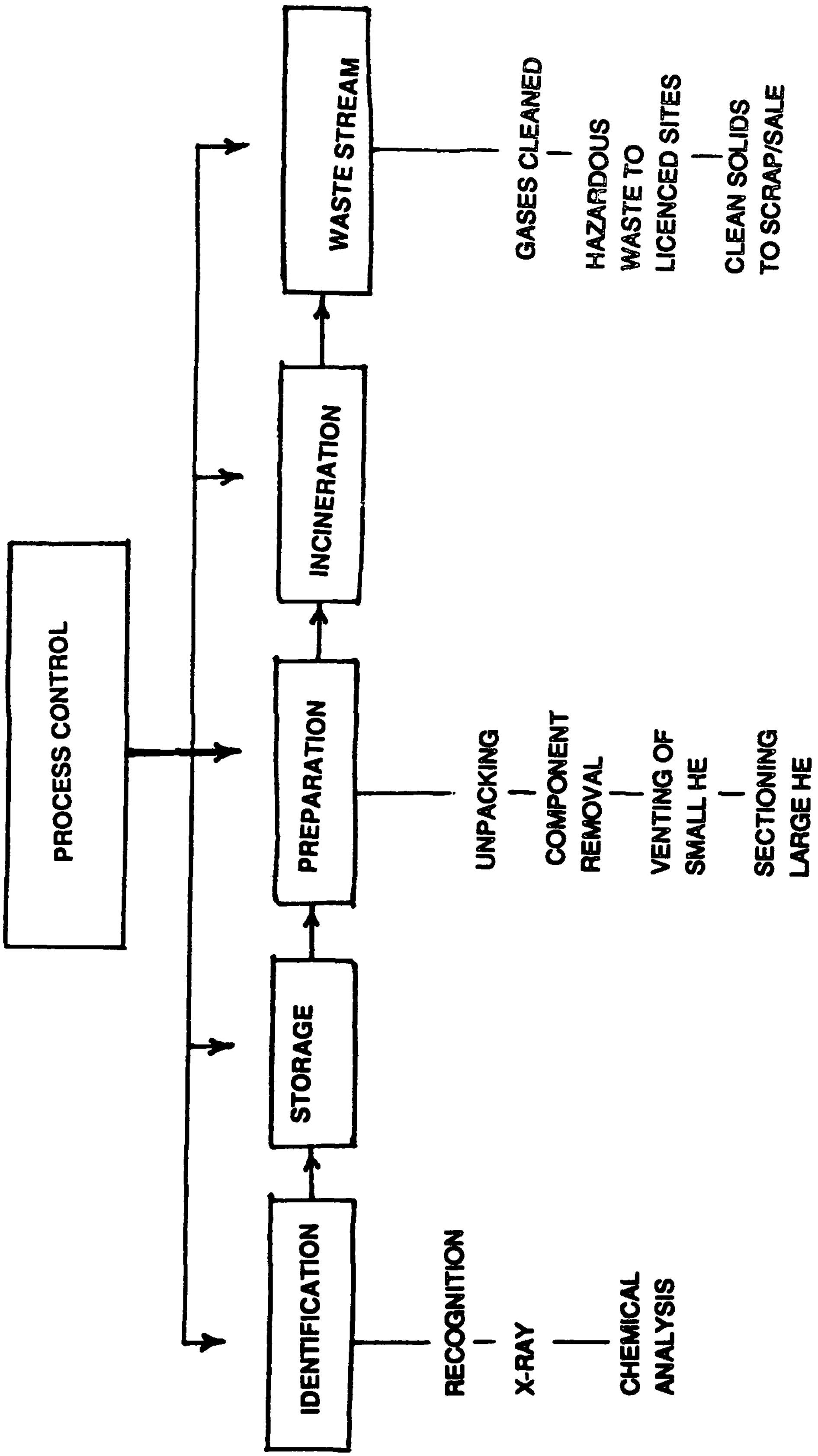
PROCESS CONTROL
IDENTIFICATION
STORAGE
PREPARATION
INCINERATION
WASTE STREAM
RECOGNITION
X-RAY
CHEMICAL ANALYSIS
UNPACKING
COMPONENT REMOVAL
VENTING OF SMALL HE
SECTIONING LARGE HE
GASES CLEANED
HAZARDOUS WASTE TO LICENCED SITES
CLEAN SOLIDS TO SCRAP/SALE

Diagram 1.

ENVIRONMENTALLY ACCEPTABLE DISPOSAL OF MUNITION AND EXPLOSIVES

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Summary.

Conventional methods of disposing of munition and explosives such as dumping at sea and open-pit burning can no longer be tolerated in view of new environmental protection laws. Therefore TNO has investigated some alternative methods of disposal such as chemical treatment, bio-degradation and controlled burning.

Our investigations showed that controlled burning is the most applicable and promising technique. A closed furnace system is used for controlled burning. We can discriminate between rotary retort furnace, fixed grid furnace and fluidized bed furnace. The advantages and disadvantages of the different systems are given. The fluidized bed furnace seems the most suitable for the situation in the Netherlands.

Connected to controlled burning is the disassembly of medium and large calibre munitions.

Many techniques are available, for example punching, shearing, sawing, and cutting. We obtained very good results using a water jet. Because all possible munition articles can be opened in a short time, it is a very safe method and the explosive can be subsequently washed out and made into a slurry. This slurry can be pumped into the fluidized bed furnace.

Additional scrubbing systems (dry chemical/wet) are needed to remove the remaining hazardous products such as HCl, SO_2, NO_x.

Calculations for a complete disposal unit have been made.

1. Introduction.

Explosives are the active constituents in munition; their stored chemical energy can be used at the right time and place by means of the unique functioning of the munition fusing system. The characteristic reactions of explosives result in high reaction rates and high pressures. This causes a continuous threat to the environment regarding explosion safety, as munition may react accidentally due to heat, friction, shock and fragment or bullet impact. Because of this, munition must be disposed of at the end of its lifetime.

Munition was often disposed of by dumping it at sea. However, more recently disassembly and subsequent burning was used. These techniques pollute the environment and are therefore no longer acceptable. New techniques such as chemical and biochemical treatment were investigated in the laboratory; the state of the art of this research is briefly described. The most suitable disposal method is controlled burning. Special attention will be focused on the rotary retort furnace and the fluidized bed furnace.

As burning explosives produces many toxic gases there will be a need for specific measurements for the decomposition or the absorbance of these gases. Addition of catalysts, wet and dry scrubbers will be an integrated part of the disposal facility for munitions.

Finally some calculations are made to compare the costs of the different systems.

2. Quantitative description of the problem

Only a small amount of the in-service munition is used during exercises: most munition will remain in storage for its entire lifetime. This period can extend over 30 years.

Due to the recent political developments in Europe, an extra amount of munition has become superfluous.

A second source of munition and explosives is the World War II items still found daily in extensive numbers in the Dutch soil. An added problem here is the bad condition of these items; they may be severely damaged, the explosive may even be mixed with soil.

A third source is formed by out-of-date explosives from industry, or industrial intermediate compounds with explosive properties, and explosives or articles filled with explosives confiscated by the authorities (e.g., illegal fireworks).

Table 1. Annual amounts (kg) of regular explosives to be disposed of by the Dutch Army, Navy and Air Force

Explosive	Army	Air Force	Navy
Propellants	10700	800	5800
High explosives	150	5700	1200
Pyrotechnics	40	460	950

Table 2. Annual amounts (kg) of explosives and munition from WW II and out-of-date industrial explosives and fireworks

Fireworks	42000
Contaminated waste	200000
Fuses	20000
Small calibre munition	20000
Medium calibre munition	3000
Large calibre munition	30000
Bombs/mines	25000
Rockets	10000
Bare explosions	30000

3. Methods of disposal

Dumping

The most common way to dispose of obsolete munitions was to dump them in isolated areas, preferably into deep trenches in the sea. The explosion risk will be minimized as the number of necessary munition handling steps is limited. It is obvious that dumping is a temporary and short-sighted solution to the problem; sooner or lat.ı we will be confronted with the consequences. The metal parts can react slowly with the environment and eventually the explosive and toxic contents will leak into the water. Pieces of munition can be picked up by fishermen, causing casualties. People bathing in the sea are at risk of being contaminated with chemical agents such as mustard gas.

Open-pit burning

A better solution to the problem is the more elaborate treatment of munition by dismantling and consequent burning of the explosive materials. The grenades can be separated easily from the cartridges; the propellant can be collected, the grenades defused and the explosives can be melted out if TNT or TNT-bases are involved.
The collected explosives, propellants and pyrotechnics are burned separately and in limited amounts in the open air, mostly at military proving grounds. This method is dangerous for the people in charge of the disposal and harmful to the environment. The toxic reaction product will pollute the air, soil and ground water.
The melting out of the explosives also results in water polluted with TNT which then has to be treated.
TNO has quantitatively studied the environmental burden as a result of open-pit burning in the Netherlands; this resulted in advising the Ministry of Defence to use a controlled burning facility, as the threshold values for many toxic components were exceeded, e.g., HCl, HF, Cl_2, SO_2, NO_x, lead, antimony, other heavy metals.

Bio-degradation

Several investigators have studied the possible use of micro-organisms, bacteria, to decompose the organic explosives (references 1, 2, 3, 4). The general conclusion from their work is that, in some cases, it is possible to decompose explosives to non-explosive components. However, these components are very toxic in the intermediate stages of decomposition (the formation of aromatic nitro-amines). Furthermore the decomposition is very slow and as such not suitable for treating large amounts of explosives.
Another problem is the diversity of the explosives present in munition and the various conditions in the soil (temperature, acidity, percentage of oxygen, other chemicals). Inorganic components cannot be treated in this way at all.
Further research will be necessary to turn biodegradation into a fully applicable method to dispose of explosives.

Chemical treatment

This is in fact the reverse route from the synthesis of explosives. For some inorganic explosives this is the best and safest method to follow. A good example is the neutralization of Azides by treatment with $NaNO_2$. However the method is difficult to apply to organic explosives; it causes an explosion risk and, at the end, we have some toxic compounds which need further treatment. The best chemical reaction seems to be the treatment with excess oxygen at elevated temperature; this process is known as burning. A necessary condition is the possibility to control the time and place of burning. We call this controlled burning. As controlled burning is the most promising and complete technique, we will deal with this in more detail in section 5. A necessary condition for the controlled burning is the pre-treatment, we therefore give a short overview of the pre-treatment techniques.

4. Pre-treatment

Good separation of the explosive and the metal parts of the munition is mandatory for a more economic disposal procedure. In this way materials can be partly reused and the controlled burning will be more efficient.

Dismantling is the conventional pre-treatment of munition: it is the separation of the grenades from the cartridges and the collection of the explosives (see Open-pit burning).

Punching can be used for small pieces of munition with medium wall thicknesses. This method is used frequently to destroy chemical munitions.

Shearing is used to remove the fuse and booster from the grenades and to cut the rocket motor into smaller sections. The shearing is done with a guillotine-like shear blade.

Sawing or cutting is also used to open munitions.

Cryo-fracture works by cooling munition by immersing it in liquid nitrogen. At such a low temperature the metal from the grenades becomes brittle and can easily be crushed by hydraulic presses. The explosive and the metal parts can then be separated.

Water jet cutting is a powerful variance on the conventional metal cutting tools. Using a high pressure water jet and abrasive, metals can be cut at high speed. Nevertheless it is a relatively safe method as the water cools the metal and possible ignition of the explosive is suppressed.
At PML-TNO we opened all different types of munition successfully with this technique (see figures 1 and 2).

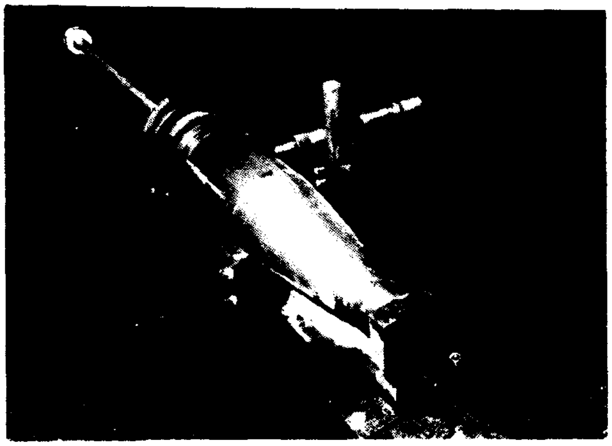

Figure 1. Test set-up for water jet cutting 155 grenade

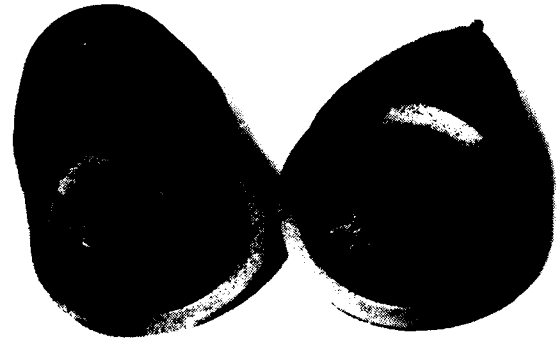

Figure 2. 155 grenade after water jet cutting

5. Controlled burning

The principle of controlled burning is the well-defined feed of munitions to a closed burning chamber or furnace. In this way the explosives can react with excess air to give the cleanest products. This, in connection with the further treatment of the reaction products, satisfies the threshold values defined in the National Environmental Protection Laws.

At the same time, the amount of explosives present in the furnace can be regulated to avoid pressures that can damage the furnace.
For controlled burning we can use three types of furnaces: rotary retort, fluidized bed, grid furnace.

Rotary retort
Controlled burning can best be described by looking at an existing system that was developed by the U.S. Army Ammunition Equipment Directorate in Tooele, Utah (see figure 3 and reference 5).

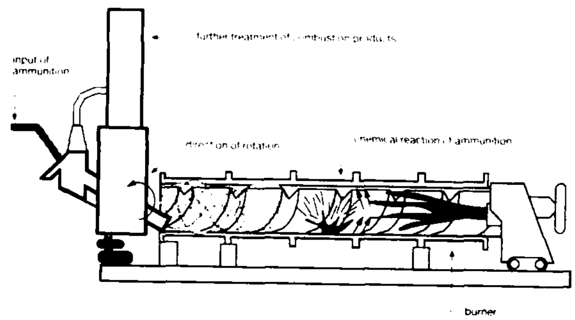

Figure 3. Principle of the Tooele Furnace

A conveyor belt transports the articles to the entrance of the furnace; from this point the munitions are transported by the spiral flight of the rotating furnace. On the other side of the furnace a burner is installed which can be fuelled by various means (fuel oil, natural gas).
Ignition will take place at a certain place as the munitions are transported towards the high temperature region of the furnace. At the end of the rotary retort the clean-burned metal pieces are transported on a conveyor belt to the metal dump.
Some disadvantages of the Tooele furnace are:
1. The reaction of the explosive is discontinuous in nature resulting in peak pressures disturbing the regular burning pattern. As a result, the residence time of the decomposition products in the afterburner is too short for complete clean combustion. Soot and even unreacted explosive will settle down in the cooler part of the exhaust system
2. The system can handle small amounts of fireworks and small calibre munition up to 20 mm. The larger calibres have to be opened to prevent the Deflagration to Detonation Transition (DDT).

Fluid bed
A fluid bed furnace uses a flow of hot air through a packed bed of silicon oxide particles.

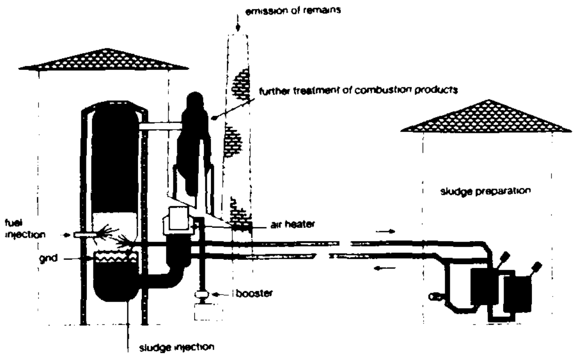

Figure 4. Principle of a fluid bed furnace

Due to the action of the air flow, the particles of the bed float and act as a liquid. The fuel is injected in or above this floating bed in the form of fine droplets, ensuring optimum mixing with air. Catalysts can be added to the bed tc facilitate the decomposition of explosives and to suppress the NO_x formation. For this reason fluid bed incineration has often been used for clean burning processes.
To be applicable for the disposal of munition, pre-treatment of the munition is mandatory. A combination with water jet cutting seems promising; the explosive is separated from the metal parts and ground to a slurry under water. The slurry is collected in a reservoir and transported to the furnace by pipes and injected in the bed.

Grid furnace
This type of furnace is used to dispose of domestic waste. The advantages are: flexibility and low cost.
Disadvantages: incomplete burning due to oxygen deficiency. Moving grid is vulnerable. Explosives can pass the grid without reaction. The latter phenomenon makes it unsuitable for the disposal of explosives.

6. Exhaust cleaning

We have seen that the solid reaction products can be collected in a cyclone or a bag house, while the gaseous products are emitted through the exhaust stack.
Explosives can react with oxygen producing harmless substances such as CO_2 and H_2O. However, depending on the composition of the explosive, there will be toxic compounds formed such as NO_x, CO, HCl, HF, SO_2. Research on a laboratory scale by ICT Germany (reference 6) has provided some data for the burning of the most common explosive materials.

Table 3. Gases formed during burning of explosives (w %)

Explosive	NO_x	HCl	SO_2	H_2S
Single base	10	-	-	-
Double base	19	-	-	-
TNT	0.01	-	-	-
Rocket prop.	-	25	-	-
Black powder	-	-	0.1	6-8

At PML-TNO we have found 3-7 weight % NO_x for TNT and 2-3 weight % for a Single Base Propellant; it is obvious that the reaction largely depends on the conditions in the furnace.

In the Netherlands the gaseous exhaust products should fulfil the following limits:

Table 4. Dutch threshold values for exhaust gases

Component	Threshold (mg/m^3)
Total solid dust	5
HCl	10
CO	50
SO_x	40
NO_x	70
Heavy metals	1
Cd/Hg	0.05
PCDs (dioxines)	0.1 nanogr. TEQ/m^3

Removal of CO/C_xH_y
This can be achieved by the correct functioning of the afterburner section: temperature above 850 °C, percentage of oxygen above 6 vol %, residence time more than 2 seconds.

Removal of NO_x
By careful design of the furnace burners and the use of clean fuels such as natural gas, the excess formation of NO_x caused by the reaction between N_2 and O_2 can be suppressed. Furthermore NO_x can be decomposed using catalysts. This is most easily achieved in the fluidized bed furnace. Other possibilities are the chemical binding of NO_x with NH_3 and the wet scrubbing technique.

Removal of HCl, SO_x
This can be done by using a wet scrubber in combination with a chemical scrubber (Na_2CO_3).

Removal of dioxines
During the combustion processes of explosives, all the necessary conditions are present for the formation of dioxines. Suitable techniques for the removal of dioxines are: injection of active carbon together with CaO, and the use of active carbon filters (see reference 7).

7. Cost estimate for complete design

The following calculations were made for the situation in the Netherlands (based on the annual figures given in tables 1 and 2), all prices in K fl.

Table 5. Cost calculations

Element	Fluidized bed	Rotary retort furnace
	1000	4500
Water jet cutting	220	220
Mill for fireworks and small calibre	100	
Control apparatus	300	150
Scrubber (wet)	175	175
Denox (chem)	50	50
Dioxine filter	50	50
Site preparation	1155	1355
Total cost	3050	6500

The investment cost of the furnace dominates the total cost; the fixed capacity of the rotary retort exceeds the annual Dutch need many times, whereas the fluidized bed furnace can be tailored to the actual needs.

For the fluidized bed the annual exploitation costs are calculated at 1000 K fl.

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RESULTS OF TRIAL TEST BURNS ON ARMY DEACTIVATION FURNACES UPGRADED TO MEET RCRA

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ABSTRACT

In 1987 the Department of Army started the process of upgrading the Ammunition Peculiar Equipment (APE) 1236 Deactivation Furnace to meet the regulatory requirements of the Resource Conservation and Recovery Act (RCRA). The furnace is used to dispose of class 1.1, 1.2, 1.3 and 1.4 munitions which are classified as hazardous waste. The upgrade has been ongoing nationwide for the past four years. This paper presents data from three trial burns which have occurred and information on the status of Part B permits for the upgraded sites.

INTRODUCTION

A Part B permit is required under RCRA for the operation of hazardous waste incinerators. The Army has been involved in upgrading facilities and performing trial burns to obtain part B permits for the furnace operations. A paper presented at the 24th DoD Explosive Safety Seminar in 1990 introduced the project and detailed the equipment upgrades required by these facilities to meet RCRA standards. Most of the facilities being upgraded have the hardware installed to operate within RCRA. The remaining hurdle to be cleared is completing the trial burn and obtaining a Part B Permit.

BACKGROUND

Nineteen sites were originally selected to be upgraded to comply with RCRA. Of the sites, three have been deleted. Installation of equipment is complete at ten sites and the remaining six sites are either underway or being reevaluated. Of the upgraded sites, three (Kansas, Lake City and Iowa Army Ammunition Plants) had their Part B permit application submitted and a draft permit approved prior to Nov of 1988. Tooele Army Depot and Anniston Army Depot both had permits submitted but did not have an approval draft. The remaining sites did not have a Part B permit application submitted for review. Today, only the original three sites have a Part B permit in place or pending.

PROJECT STATUS

The original project required installation of equipment and controls costing approximately $1M per site. Several sites were deleted in the early stages of the project due to cost and/or being on the base closure list. The remaining sites have been proceeding for nearly four years to obtain a Part B Permit. The actual installation of hardware is nearly complete with only six sites remaining to be done. These sites are on schedule and should be complete within two years.

The Part B Permits for Iowa, Lake City and Kansas were submitted early and a draft permit approved. Tooele and Anniston are both near approval on their draft permit, but in both cases it has been a lengthy difficult process. Seven sites submitted their permits in 1991 and are either awaiting review by the State or are in the process of answering Notices of Deficiency. With the exception of the three AAP sites there is no current accurate estimate on when any site will actually receive a draft permit or be allowed to proceed with a trial burn.

Trial burns have been performed at Lake City AAP and Iowa AAP. The trial burn for Kansas is scheduled for early 1993. Lake City completed their trial burn and has an approved Part B permit to operate their furnace. Iowa has approximately six more hours of burn time to complete the required data collection for final submission to the state. Tooele performed a mini-burn in 1988 and the results of that burn are also included in the report.

The original permits for the other seven sites were prepared under contract to the Corps of Engineers, Huntsville Division. There have been significant additions to most of the original permit applications due either to requests for more information by the states or due to changing regulatory requirements.

The Army Environmental Hygiene Agency (AEHA) prepared a model trial burn plan which has been used in the permit applications. Experience indicates that this has been a good starting point. Most permits have required modifications to the original trial burn plan and to other sections to answer concerns of the regulators. This has been a difficult, lengthy effort with no immediate relief in sight. Heightened concern about public comment and increased awareness of possible hazards have caused the regulators to take a very cautious approach to approval of draft permits.

Part B Permits are based on emissions to the atmosphere. Permit limits are based on either total allowable emissions, percent emissions, or hazards to the surrounding community. Modifications to the original permits were often driven by the regulator's desire to ensure a high probability of success during the trial burn.

Since there are no real-time particulate or metals monitors either currently available or of a high level of dependability, the permits control feed, operating parameters and monitor CO and O_2 out of the stack to ensure compliance.

Many sites felt they had good relations with the state agencies and could obtain draft approval within a few months of submission of the permit. This has proved to be inaccurate. The average time for approval of permits is approaching 3-4 years and with an increased number of applications and regulatory requirements this may get worse.

Of the sites which have made significant progress on permit approval, the trial burn plans have become a key issue in assuring the regulators that the site meets emission standards. Because of this concern the trial burn plans have received close scrutiny and are representative of worst case feed stock to the APE 1236 furnace.

The approved trial burns have been based on a selection of materials which would represent the worst case for different items of concern. The items selected have been considered to represent worst case for particulate metals, principle organic hazard constituents, and chlorine.

(See Table Summary of Trial Burn)

CONCLUSIONS

APE 1236 furnaces can meet RCRA standards for burning of munitions. The sites have demonstrated that compliance with current standards for POHC, particulate, and metals and chlorine can be achieved by the upgraded facility.

The permitting process itself is the real problem. The time needed to assemble and submit a permit is very lengthy often in excess of a year. This is just the beginning. It can take 3-4 years after the original submission to answer all the notices of deficiency.

Several sites have gotten into an escalating situation where answers to NODs cause new questions requiring more information again raising new questions. The circle must be broken if these sites are to complete the permitting process and get back to work. Only two sites have actually processed munitions since November 1988.

This whole procedure requires streamlining technology and compliance with the standards is not the issue. As shown by the data presented the system can meet the current standards and technology and can keep pace with increasingly stringent regulations. This is being delayed by the permitting process. Meanwhile the ability of the Army to dispose of munitions is being severely impacted.

Table 1. FEED DATA AND OPERATING PARAMETERS

Feed Item	20mm M96	FA-956	HI-SKOR 700x	IMR 5010
Waste Feed Rate (lbs/hr)	543.68	123.80	40.47	181.94
PEP Feed Rate (lbs/hr)	86.80 (est.)	15.91	40.47	181.94
Kiln Rotation (rpm)	1.03	1.67	2.8	2.8
Avg. Kiln Outlet Temp. (deg F)	939	744	696	707
Avg. Afterburner Outlet Temp. (deg F)	1400	1350	1449	1400
Avg. Stack Gas Flow Rate (acfm)	5142	5127	5201	5192

Table 2. DRE DATA

Feed Item	20mm M96	FA-956	HI-SKOR 700x	IMR 5010
NG DRE(%)	-	-	99.998	-
DNT DRE (%)	-	-	-	99.9985
DPA DRE (%)	-	-	-	99.9937

Table 3. EMISSIONS DATA

Feed Item	20mm M96	FA-956	HI-SKOR 700x	IMR 5010
Avg. Part. Conc. (gr/dscf)	.0160	.0186	.0206	.285
Corrected CO 1 Hour Rolling Avg. (ppm)	20.42	11.07	5.32	23.42
Avg. O2 (%)	15.84	16.83	16.35	16.45

Table 4. METALS DATA (lbs/hr)

Feed Item	20mm M96	FA-956
Avg. Ag	7.02×10^{-5}	5.65×10^{-5}
Avg. As	2.82×10^{-5}	2.77×10^{-5}
Avg. Ba	1.64×10^{-3}	1.03×10^{-3}
Avg. Be	5.58×10^{-6}	5.59×10^{-6}
Avg. Cd	1.24×10^{-4}	1.23×10^{-4}
Avg. Cr	2.45×10^{-4}	6.39×10^{-5}
Avg. Hg	3.64×10^{-5}	4.68×10^{-5}
Avg. Pb	6.92×10^{-3}	6.13×10^{-3}
Avg. Sb	7.04×10^{-4}	7.44×10^{-4}
Avg. Tl	5.58×10^{-6}	5.59×10^{-6}

Summary: The particulate and DRE standards were met for all tests. Tier II Cr limits were exceeded for two runs of the 20mm. The CO level for all runs were below the Tier I level.

Table 5. FEED DATA AND OPERATING PARAMETERS

Feed Item	20 mm M96	M1 Prop.	M7 Prop.	M1/HCB/METALS
Kiln Rotation (rpm)	2 rpm for all runs			
Avg. Afterburner Outlet Temp. (Deg F)	1202 for all runs			

Table 6. DRE DATA

Feed Item	20 mm M96	M1 Prop.	M7 Prop.	M1/HCB/METALS
NG DRE (%)	-	99.998	-	-
DNT DRE (%)	-	-	99.998	-
HCB DRE (%)	-	-	-	97.27

Table 7. EMISSIONS DATA

Feed Item	20 mm M96	M1 Prop.	M7 Prop.	M1/HCB/METALS
Avg. Part. Conc. (gr/dscf)	.0.145	.044	.038	.036
Corrected CO 1 Hour Rolling Avg.	Low of 53.8 ppm to high of 333.9 ppm			
Avg. O2 (%)	16.52 - 16.53 for all runs			

Table 8. METALS DATA

Feed Item	M1/HCB/METALS (lbs/hr)
Avg. Cr	4.95x10-5
Avg. Pb	15.90x10-3
Avg. Sb	0.90x10-3

Table 9. HCL DATA

Feed Item	M1/HCB/METALS
Feed Rate	5.85 lbs/hr HCB
Emissions	1.06 lbs/hr HCL

This equates to 24.5% of chloride emitted to atmosphere as HCL. It is estimated that 16.5 lbs/hr of chloride could be fed without exceeding HCL Tier I emissions rates.

Summary: The incinerator had no trouble meeting the DRE for NG and DNT at 1200 Degrees F but did not achieve the DRE for HCB at that temperature. The temperature should be raised to 1400 degrees F to test with HCB for DRE. At the feed rates used during this assessment the Cr and Pb levels were exceeded. The bags in the baghouse did not appear to be properly coated and should be caked more thoroughly for further tests. The chloride being fed at this rate is well below the RCRA Tier I standards for emissions.

Table 10. FEED DATA AND OPERATING PARAMETERS

Feed Item	TNT	PDX 0280	Comp H-6
Waste Feed Rate (lbs/hr)	497	489	356
PEP Feed Rate (lbs/hr)	198.83	199.66	270.91
Kiln Rotation (rpm)	1.03	1.67	2.8
Avg. Kiln Outlet Temp. (deg F)	793	548	593
Avg. Afterburner Outlet Temp. (deg F)	1445	1411	1413
Avg. Stack Gas Flow Rate (acfm)	2399	2795	2373

Table 11. DRE DATA

Feed Item	TNT	PDX 0280
DRE(%)	99.9985	99.9999

Table 12. EMISSIONS DATA

Feed Item	TNT	PDX 0280	Comp H-6
Avg. Part. Conc. (gr/dscf)	.0054	.00448	.0121
Corrected CO 1 Hour Rolling Avg.	53	8.3	7.7
Avg. O2 (%)	16.68	17.67	17.64

Table 13. METALS DATA (lbs/hr)

Feed Item	TNT	PDX 0280	Comp H-6
Avg. Cr	2.64x10-6	7.46x10-6	5.27x10-6

Summary: The particulate emission were well below the RCRA standard. DRE for all runs of TNT and RDX exceeded the RCRA standard. The corrected CO value for PBX and Comp H-6 were below the tier I level. Two of the runs for TNT were above the Tier I level. This was probably due to an afterburner flame out during the TNT run.

Paper Presented at the:

Twenty-Fifth DoD Explosives Safety Seminar
Anaheim, California

SOIL REMEDIATION METHODS

by

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ABSTRACT

Remediation methods, problems and optimization techniques for removal of propellants, explosives and pyrotechnics in soils are discussed. Process flow sheets to select best soil remediation methods plus an example of optimization are presented. Many parameters which effect remediation are discussed.

INTRODUCTION

In the past, waste propellants, explosives and pyrotechnics (PEP) would be burned in open pits or recovered if economically feasible. In many manufacturing, loading and end use applications, residual and scrap was landfilled, placed in leaching ponds for separation from water and other chemicals, or accidentally spilled or deposited onto adjacent land. Within the last fifteen years, great emphasis was placed on removal of the hazardous PEP from the soils and ground for safety (potential fires or explosions) and environmental protection (chemicals in water system). Each propellant, explosive or pyrotechnic in the soil presented different issues regarding soil remediation. Much emphasis today is on incineration to destroy the PEPs at significant cost and effort. In this paper, we review the issues related to soil remediation and present optimization methods.

PROBLEM DEFINITIONS

When it is known that propellants, explosives or pyrotechnics are in the ground, various ways to remediate the situation are possible as follows:

- Leave it and treat it
    - neutralize
    - decompose

- Dig it out and
    - burn it
    - decompose it
    - recover it

- Wash it out and
    - burn it
    - decompose it
    - recover it

- Add diluent to soil to reduce hazardous concentrations

Before any remediation is attempted, study is necessary to identify the seriousness of hazard and ways to remedy the situation. A flow chart showing the remediation optimization process is illustrated in Figure 1. Basically, the process steps are as follows:

1. Characterize and locate hazardous material and soil.

2. Remediation method study.

3. Selection of best method.

4. Follow through.

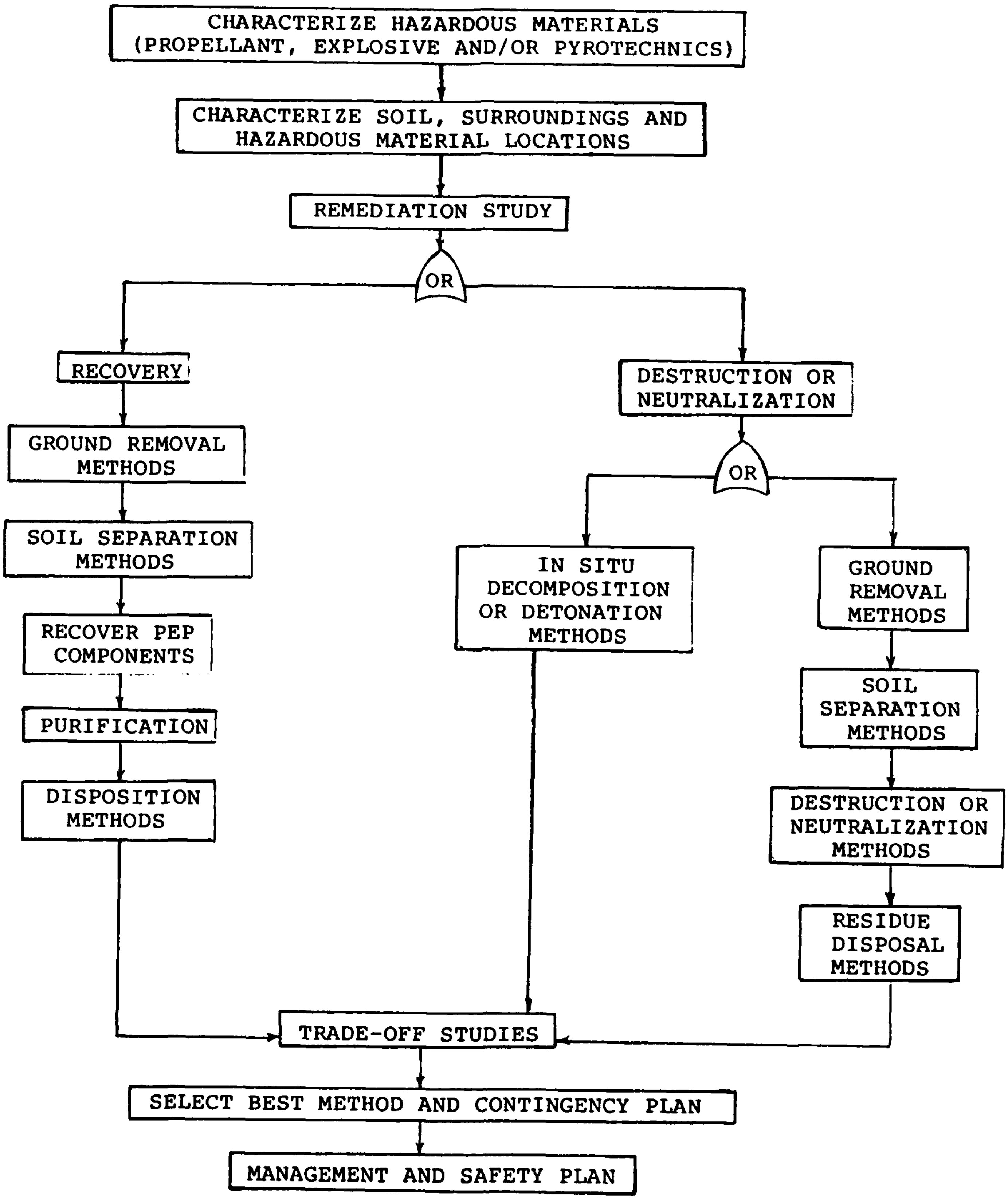


Figure 1. Soil remediation optimization process.

The PEP characterization consists of identifying its physical, chemical, thermal, electrical and ignition sensitivity properties (see Figure 2). Since the hazardous material may be mixed with other explosives, propellants, or pyrotechnics and/or other chemicals, PEP compatibility analysis is necessary to identify the effects on sensitivity to initiation, stability and quality.

Soil sampling is usually necessary to determine location and condition of the PEP in the ground. Core samplers can sometimes give erroneous results especially if used in sandy soils, i.e., the core can plug up with sample sufficiently to permit soil to flow by the core as it descends into the ground. If large pieces of PEP are present, soil coring may be very dangerous causing impact or friction initiation of the PEP which may propagate into a fire or explosion. Sometimes, if PEP distribution in the soil is very non-uniform, mapping from soil sampling can be very deceiving.

Seismic analysis techniques can be used to identify PEP locations provided that the seismic signals are not great enough to initiate the PEP. If large areas are contaminated with PEP, seismic methods may be more cost effective and will produce better definitions of PEP locations. Some core sampling will still be necessary to identify PEP physical and chemical conditions. Also, initiation sensitivity testing will be necessary to identify effects of changes of state, conditions and contamination of ignition sensitivity and quality. See Figure 3.

Soil remediation can be accomplished by destroying or decomposing PEP in situ or by removing PEP from the soil and recovering or destroying/decomposing it.

In situ destruction or decomposition can be accomplished by detonation, bulk decomposition or separation of components (e.g., pyrotechnics). See Figure 4. Methods to verify completion of destruction (e.g., soil borings and lab tests) may be costly, time consuming and dangerous. This in situ destruction approach may be ineffective and too costly.

Removing the PEP and soil from the ground by earth-moving equipment and/or water washout techniques will depend on its concentration and ignition sensitivity. Water washout techniques (like river dredging) could facilitate water separation of PEP from soil via hydroclones. Also, the PEP may be much safer to handle if in water-wet conditions rather than in dry conditions.

Earth removal by earth-moving equipment may be very hazardous especially if the PEP or mixture is very impact, friction or electrostatic discharge ignition sensitive. Water washdown can be used during excavating to render the PEP-soil mixture safe to handle. If high concentrations of PEP in soil (enough to cause soil to be detonable) are found, special ways to dilute or inert the PEP may be necessary. If the PEP concentration is low enough, or is brought low enough by adding more soil, (concentration below 10% of detonable limits), the soil mixture can be destroyed by

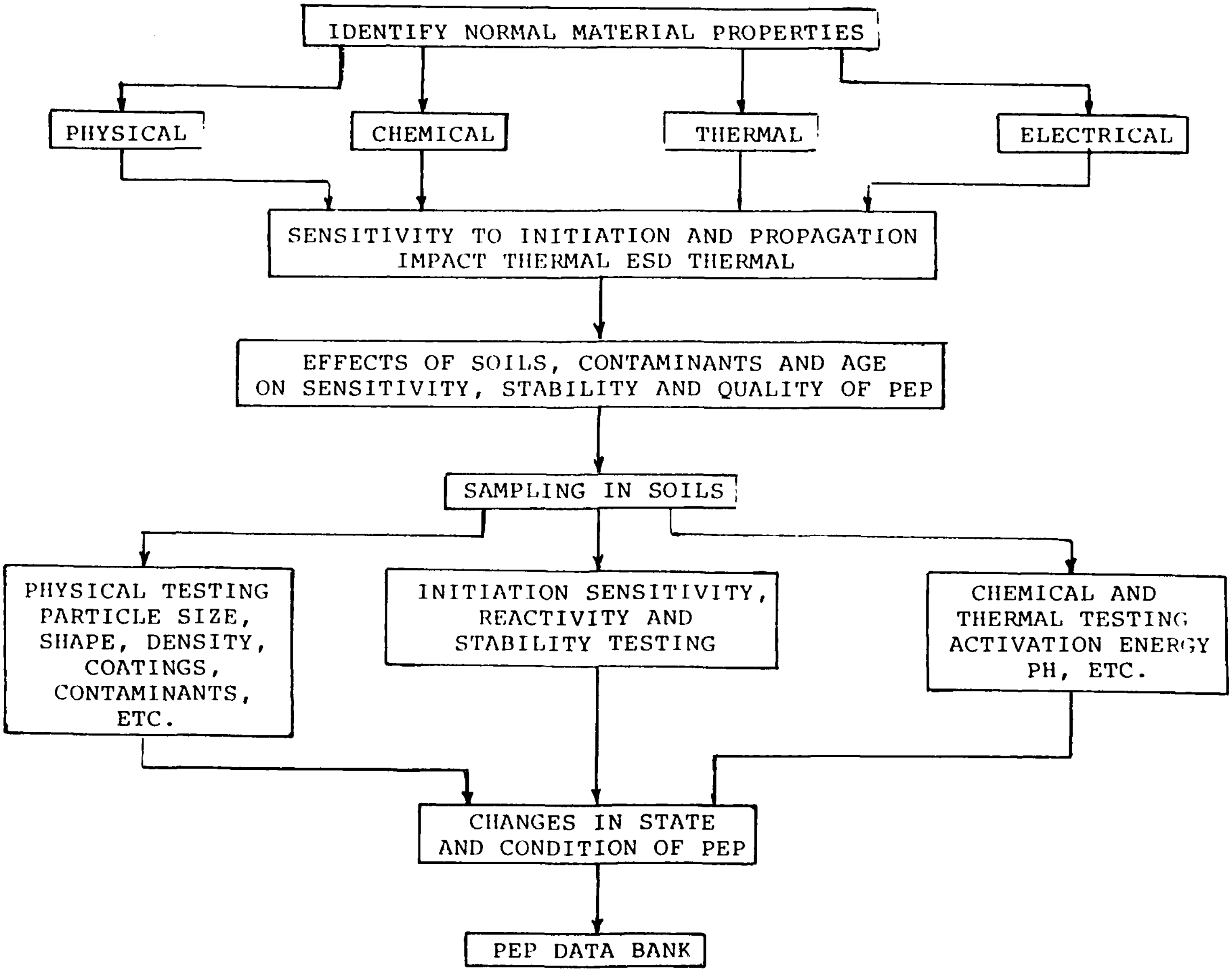


Figure 2. Characterization of propellants, explosives and pyrotechnics, (PEP) in soil.

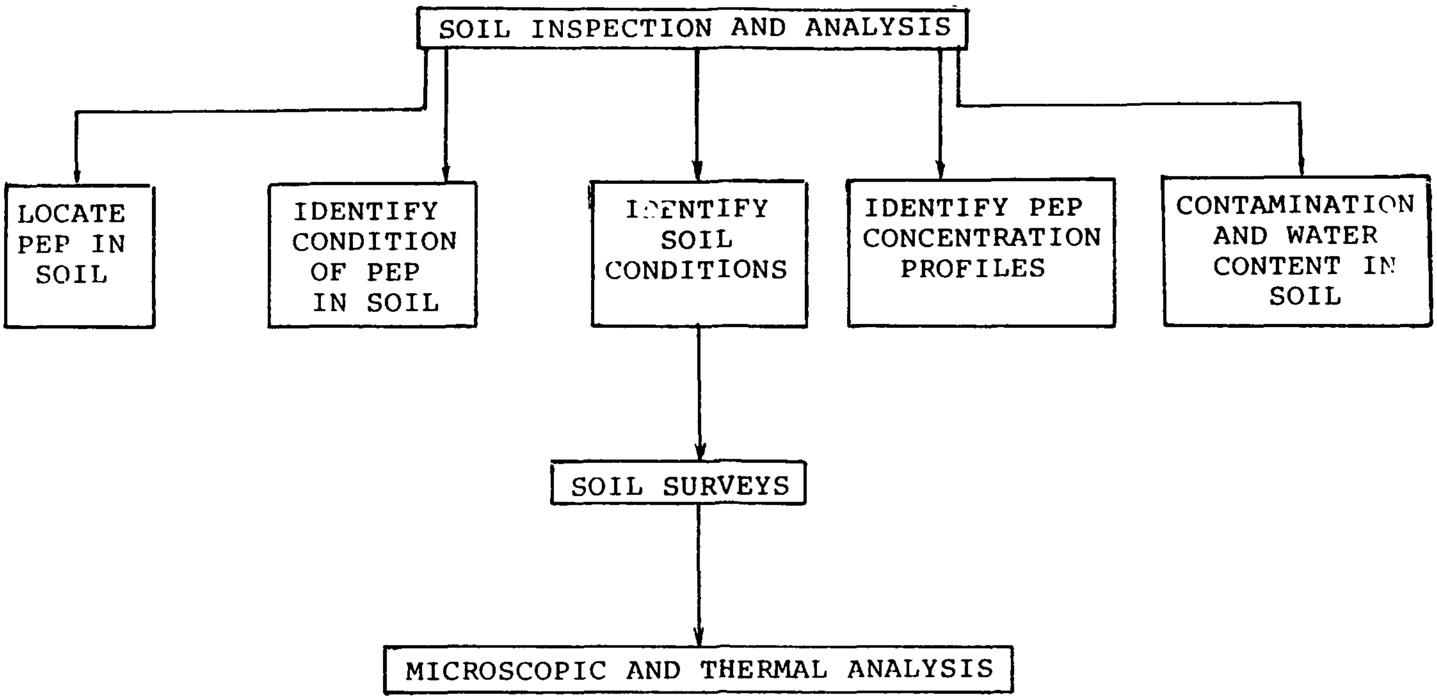


Figure 3. PEP-soil characterization.

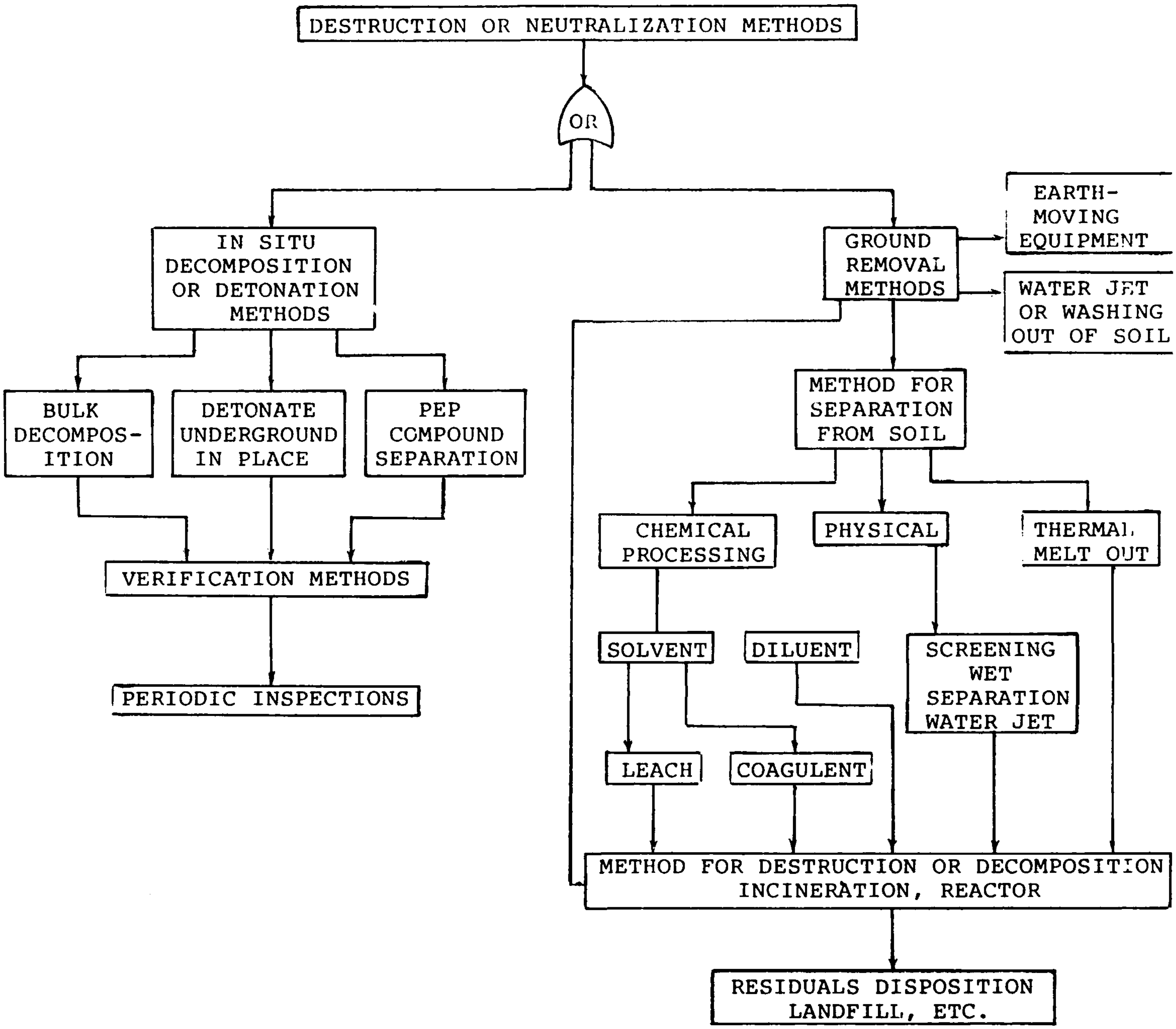


Figure 4. Remediation study - destruction.

incineration (popular today) or decomposition (or neutralization) by chemical reaction.

In either case, residual material must be disposed of properly (landfill if safe or mixing in other safe processes). For direct incineration of the recovered PEP-soil, a massive amount of residual dirt must be disposed of somewhere and extensive tests may be necessary to verify soil environmental safety.

During stockpiling of removed PEP-soil, migration can occur if the PEP particle size and density is greatly different from the soil, or the PEP is water soluble when rains occur.

Once removed from the ground, the PEP-soil mix can be separated prior to destruction by chemical, physical and thermal means. See Figure 4.

For PEP recovery process, the PEP also can be separated out by the same means as listed above. See Figure 5.

Some PEP can be separated from the soil using water soluble solvents (e.g., acetone, etc.) In this case, the solvent added to the PEP-soil mixture causes the PEP to coagulate and cling together. Later, water separation via hydroclone or screening will separate the soil from the PEP. Solvent separation from water could be accomplished by distillation at a later time.

Dry screening can separate PEP from soil, as long as it is of different particle size from the soil. If PEP is dusty, dry screening may not be safe and hydraulic (water) separation may be more appropriate.

Some PEPs can be heated to melting point and the soil can then be screened out from the liquid (e.g., TNT). Caution is necessary to characterize PEP thermal stability as encountered in the soil so that at large scale, runaway reaction can be prevented.

Once separated, the PEP will need to be in a safe condition for handling. Diluents, solvents or inerting agents may be added to assure safety and maintain quality for recovery.

A purification process may be necessary to bring the PEP quality up to standard levels. Recrystalization, solvent purification and chemical treatment may be necessary here.

Packaging and storage of purified PEP should be such that no adverse effect on safety, quality or storage aging will occur.

TRADE-OFF STUDY

The next step in identifying the best remediation method is to conduct a trade-off analysis of important selection parameters. Some typical parameters to be considered (see Figure 6) are as follows:

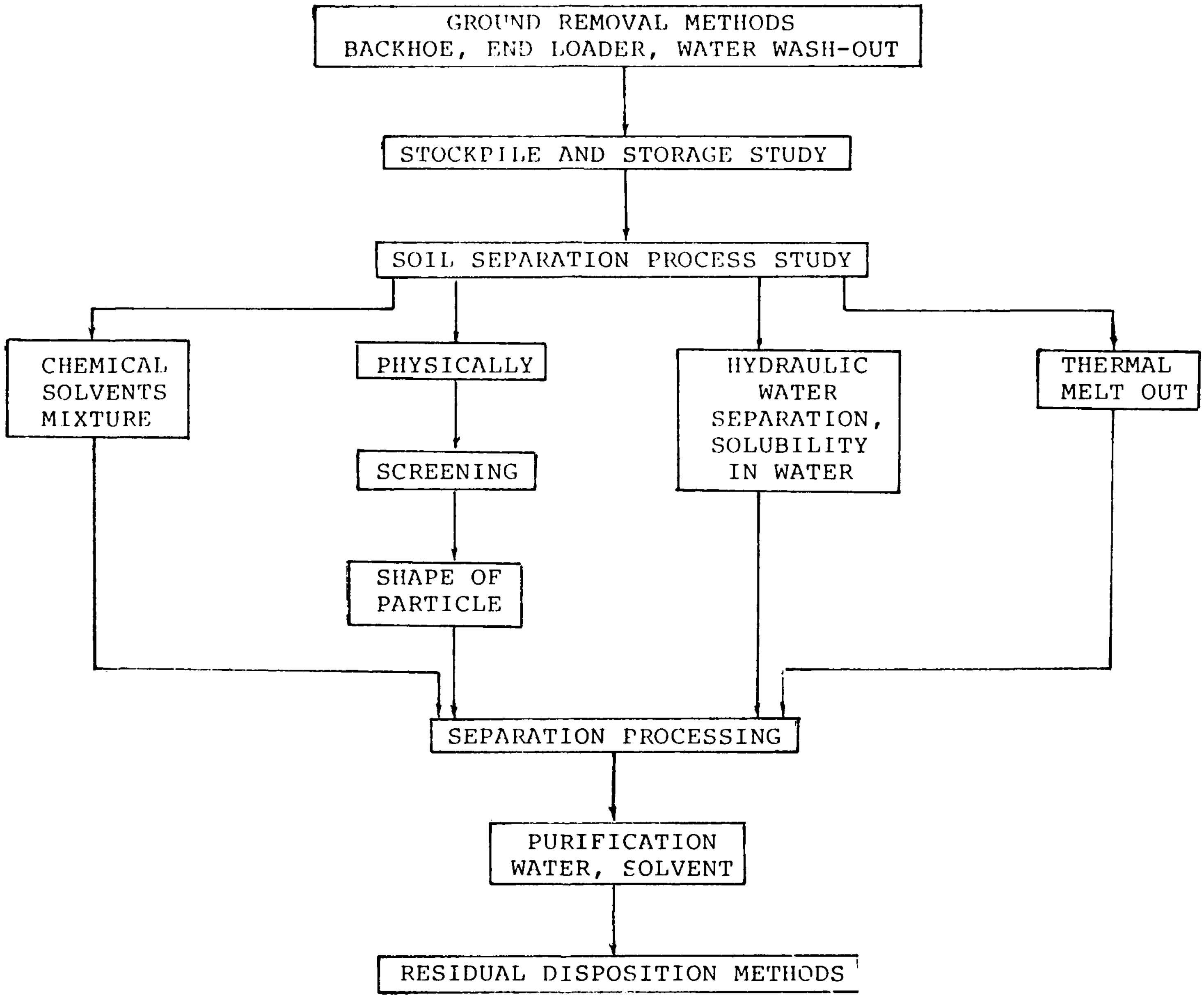


Figure 5. Remediation study - recovery.

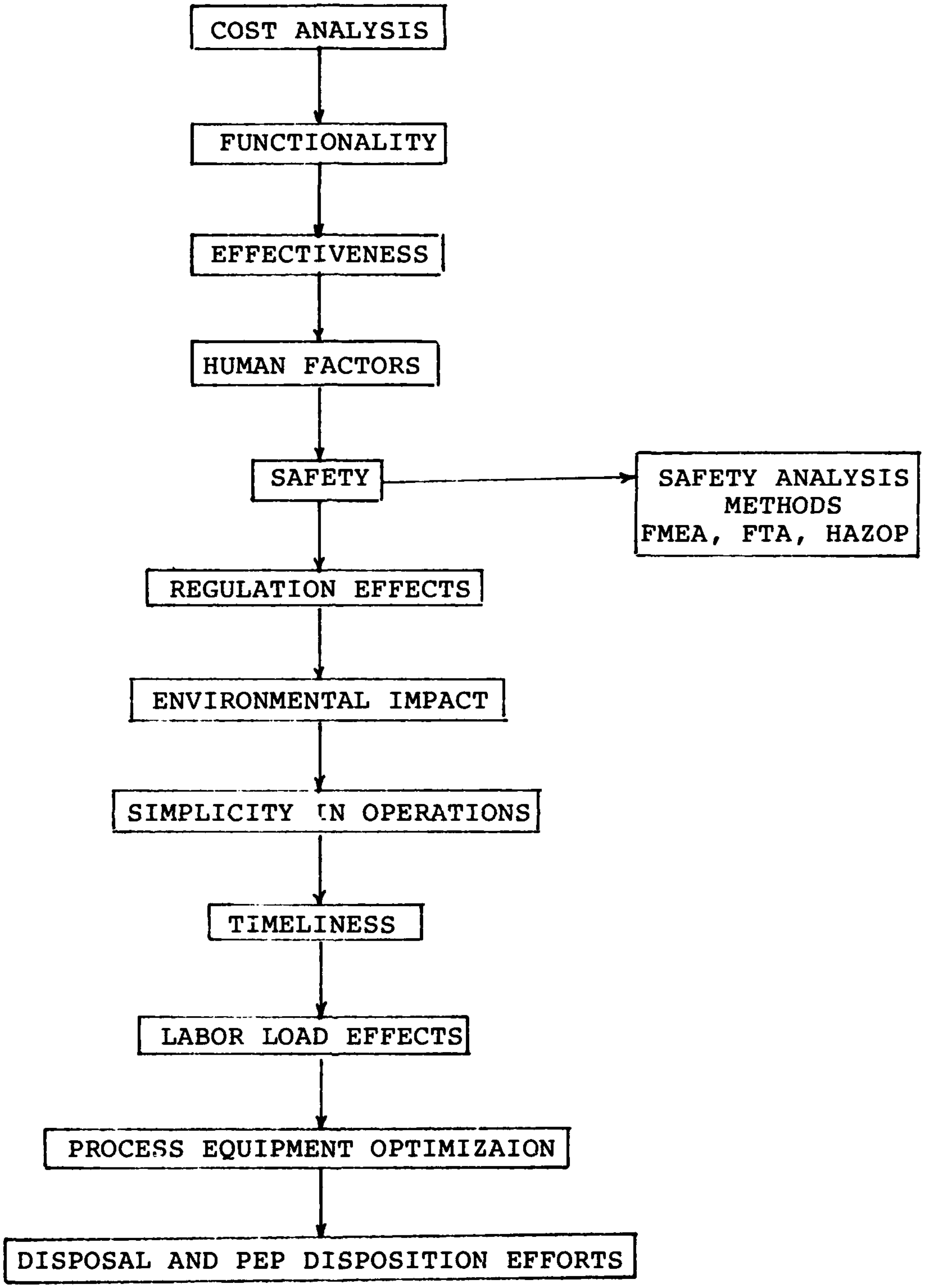


Figure 6. Trade-off study.

- Cost
- Functionality and simplicity
- Cleanup effectiveness
- Safety
- Time to complete
- Process equipment availability
- Environmental impact and regulations
- Labor availability
- Disposal or recovery ease

For each remediation method considered, estimates on cost, safety and availability of equipment and labor should be made. Preliminary hazards analysis should be conducted for each viable method to identify major safety restrictions prior to completion of the trade-off analysis. Thus, remediation methods which are too hazardous can be removed from consideration.

The relative importance of each remediation method selection parameter should be agreed upon early in the study. See Figure 7. A typical ranking multiplier for explosives in soil is shown in the following table:

TYPICAL RANKING MULTIPLIERS

PARAMETER	MULTIPLIER
Cost	10
Safety	10
Functionality and Simplicity	7
Effectiveness of Cleanup	5
Availability of Equipment	2
Availability of Labor	4
Time to Complete	5
Environmental Impact and Regulations	3

Next, each parameter is assigned a relative ranking scale to assist in evaluating its level for each remediation method. Some examples are as follows:

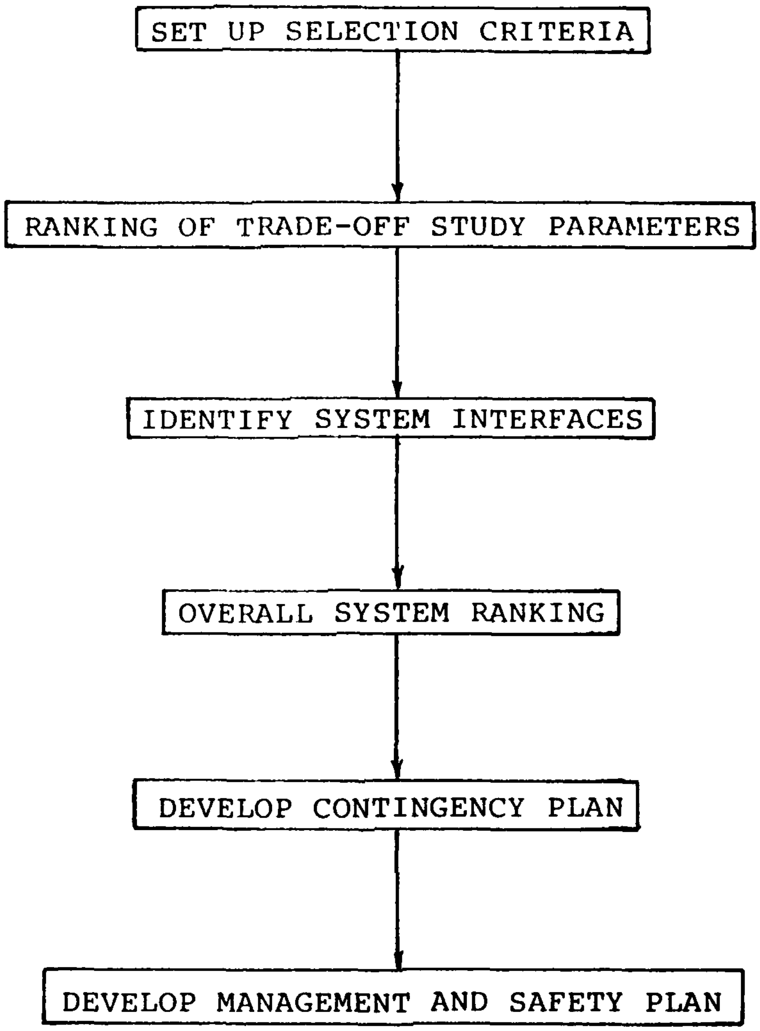


Figure 7. Selection of best method.

COST	
RANKING	DOLLARS
5	10^3
4	10^4
3	10^5
2	10^6
1	10^7

SAFETY	
RANKING	DOLLARS LOST PER YEAR
5	$< 10^3$
4	10^4
3	10^5
2	10^6
1	10^7

FUNCTIONALITY	
RANKING	LEVEL
5	Easy
4	Relatively Complex
3	Complex
2	Very Complex
1	Extremely Difficult

CLEANUP EFFECTIVENESS	
RANKING	PERCENT
5	100
4	92
3	90
2	70
1	20

AVAILABILITY OF EQUIPMENT	
RANKING	TIME
5	Readily
3	Relatively Available
1	Not Available

LABOR AVAILABILITY	
RANKING	LEVEL
3	Readily
2	Relatively Available
1	Not Available

TIME TO COMPLETE	
RANKING	TIME
3	1 Month
2	6 Months
1	2 Years

ENVIRONMENTAL IMPACT	
RANKING	LEVEL
3	None
2	Minor
1	Major

SELECTION OF BEST METHOD

The next step is assigning ranking values of parameters for each remediation method. An example for optimization is shown in Table 1 for nitrocellulose in soil which has slightly decomposed. The process options are shown in Figure 8. This is an example and each situation may require different parameter values and ranking. By multiplying each parameter ranking by the relative importance value and adding up all numerical values, an overall ranking for each method is made. The method is selected based on the highest numerical ranking value.

IMPLEMENTATION

Once the method of remediation has been chosen, management plans for various options as shown in Figure 9, should be undertaken. Contingency plans should also be formulated, since excavation could yield major changes in composition, concentration, contaminants and soil conditions which may require changed remediation methods.

CONCLUSIONS AND RECOMMENDATIONS

Various soil remediation methods have been reviewed and selection criteria and methods were given for PEPs. An example of trade-off analysis and optimization was given.

Soil remediation is very complex and can be very dangerous especially with mixtures of PEPs and other chemicals. If concentrations are high in the soil, potential detonations of PEPs could occur. Chemical, physical, thermal and hydraulic methods can be used to separate PEPs from the soil once excavated. Excavation can be done by mechanical or water washout methods. Depending on the type of PEP, destruction, decomposition or recovery is possible.

It is recommended that thorough study and trade-off analyses be conducted on contaminated soils before remediation is attempted.

Also, soil sampling is essential to be sure what is in the soil and what its condition is.

Detailed ignition sensitivity testing is essential to evaluate the hazards presented by of PEP-soil remediation. Also, detailed hazard analyses must be done on the processes and their contingencies prior to startup to assure safety. For recovery methods, great care must be exercised to be sure that the PEP is pure, free from contaminants and has not aged sufficiently to lose stability.

TABLE 1

TYPICAL TRADEOFF STUDY RESULTS FOR NITROCELLULOSE

METHOD	(10) COST	(10) SAFETY	(7) FUNCTION	(5) EFFECTIVENESS	(2) AVAILABILITY OF EQUIPMENT	(4) PEOPLE	(5) TIME TO COMPLETE	(3) ENVIRONMENTAL IMPACT	RANKING TOTALS
In situ destruction	(3) 30	(3) 30	(1) 7	(2) 10	(3) 6	(2) 8	(3) 15	(1) 3	109
Dig out and incinerate	(1) 10	(4) 40	(4) 28	(4) 20	(1) 2	(2) 8	(2) 10	(2) 6	124
Dig out and decompose	(3) 30	(2) 20	(4) 28	(2) 10	(3) 6	(2) 8	(2) 10	(2) 6	118
Dig out separate and incinerate	(1) 10	(4) 40	(2) 14	(5) 25	(1) 2	(2) 8	(1) 5	(2) 6	118
Dig out and recover	(2) 20	(2) 20	(2) 14	(4) 20	(1) 2	(2) 8	(2) 10	(3) 9	103

Select #2, Dig Out and Incinerate

Situation: Nitrocellulose and cellulose products burned in soil.

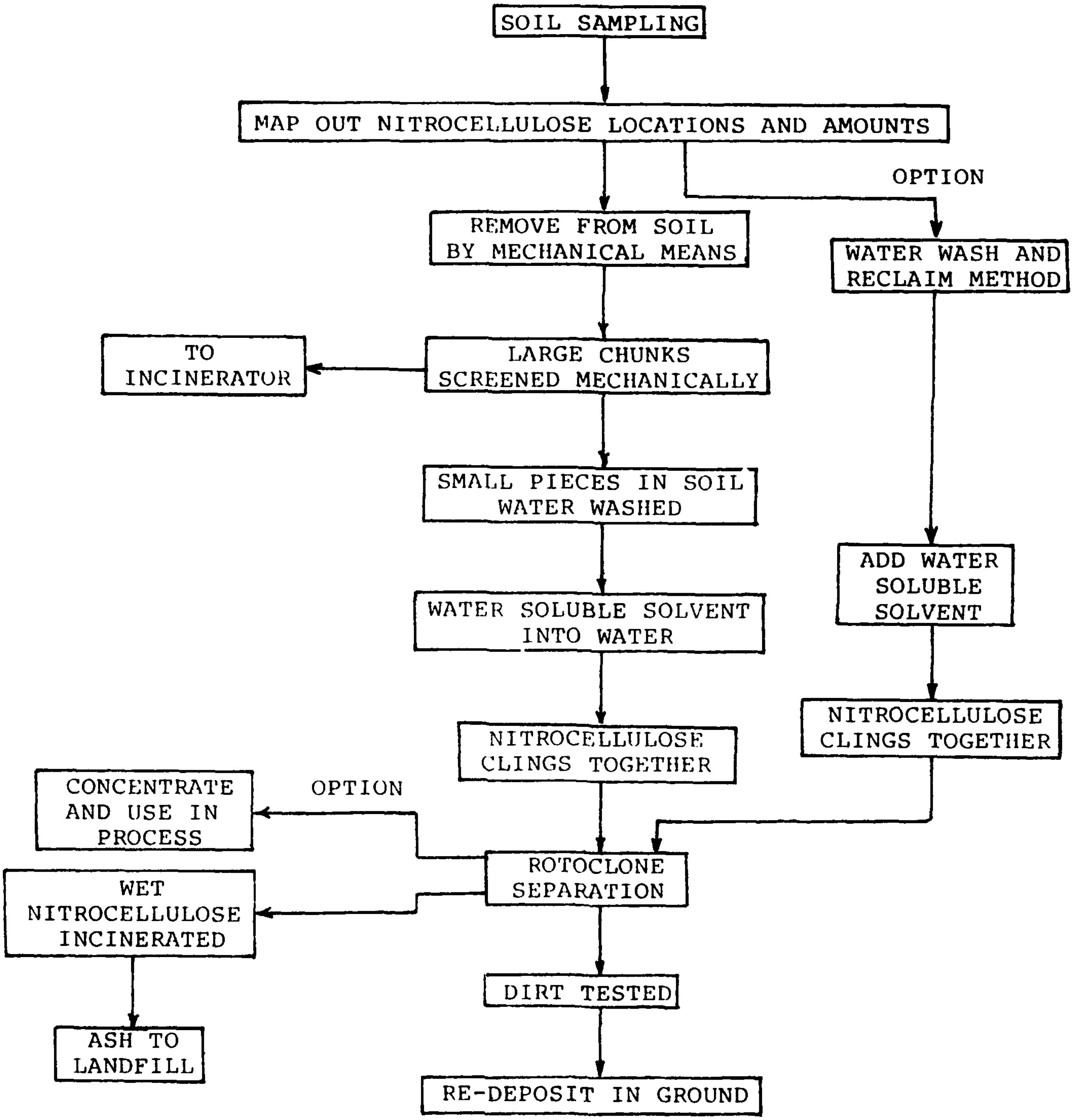
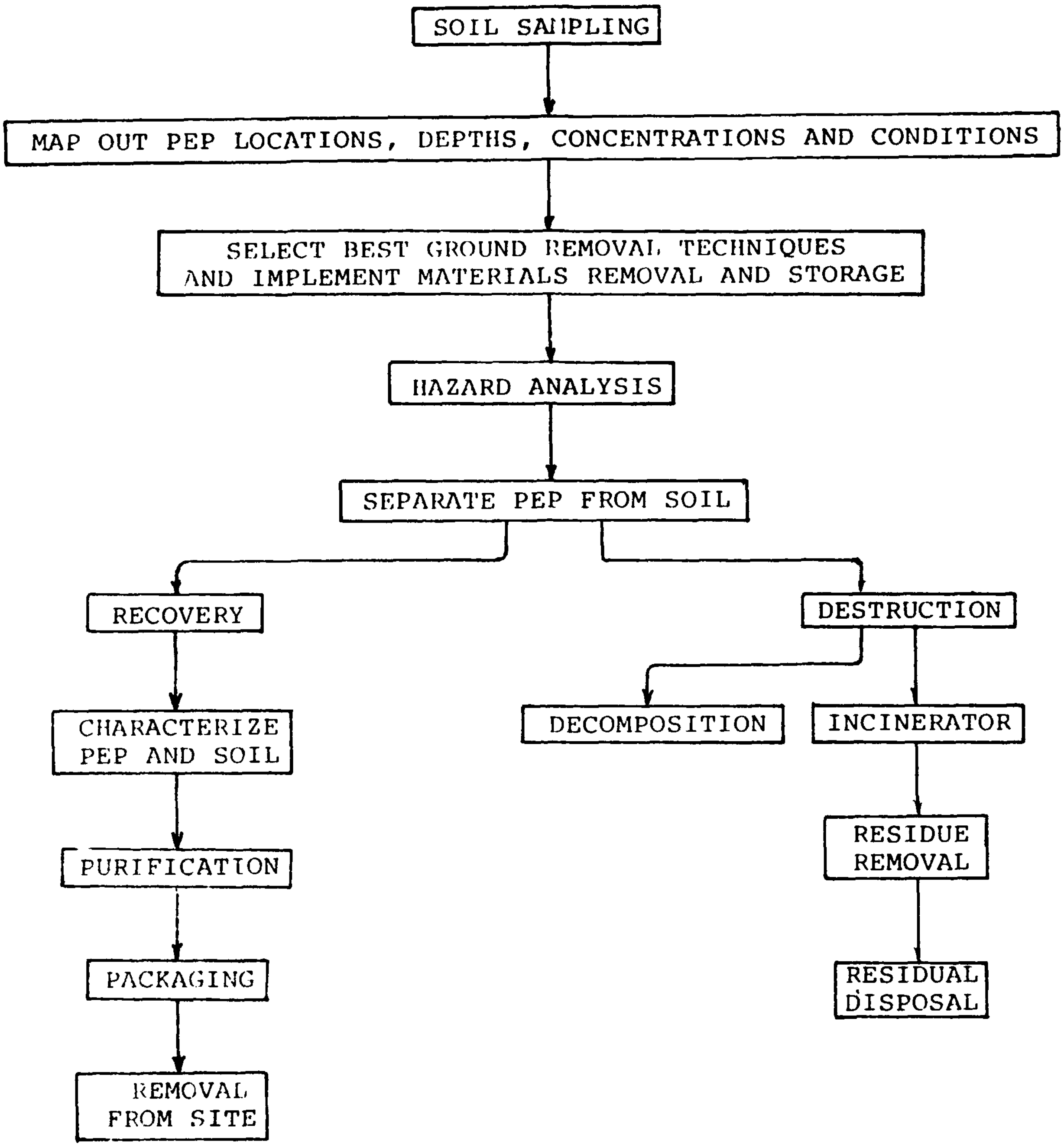


Figure 8. Typical soil remediation process.


SOIL SAMPLING
MAP OUT PEP LOCATIONS, DEPTHS, CONCENTRATIONS AND CONDITIONS
SELECT BEST GROUND REMOVAL TECHNIQUES AND IMPLEMENT MATERIALS REMOVAL AND STORAGE
HAZARD ANALYSIS
SEPARATE PEP FROM SOIL
RECOVERY
DESTRUCTION
CHARACTERIZE PEP AND SOIL
DECOMPOSITION
INCINERATOR
RESIDUE REMOVAL
PURIFICATION
PACKAGING
RESIDUAL DISPOSAL
REMOVAL FROM SITE

SOME REMARKS on a 100 Tons ACCIDENTAL EXPLOSION in TUNNEL SYSTEMS in 1965

Seppo Tuokko

Ministry of Defence, Helsinki Finland

TWENTY-FIFTH DOD EXPLOSIVES SAFETY SEMINAR

ANAHEIM, USA
August 1992

ABSTRACT

A progressive sequense of accidental explosions in a Finnish underground munitions storage facility occured in Uusikylä, Finland in 1965. The largest of these sequential events involved the simultaneous detonation of as much as 100 tons of explosives material.

Considerably more explosives material was involded in the total event (in all about 700 tons consisting TNT, RDX and gunpowder).

Soon after the Explosion a special Investigation Committee was nominated. It worked over a year before the investigation report was completed. I refer here to this above mentioned report.

REASONS FOR IGNITION

The real reason for ignition is unknown. The Investigation Committee could only make a list of possible ignition reasons.

These reasons are:

1. Fall of a stone or a block of rock from the tunnel roof upon some sensitive material.
   Statistically 1 block falls down in 10 years in these kind of Tunnels.

2. Selfignition
   In the tunnels there were materials in which it would have been possible to occur selfignition. The Investigation Committee regards selfignition probability as very low.

3. Lightning (Thunder)
   There was no special thunder in the area at that time.

4. Sabotage
   A special group of the Investigation Committee and the police worked very much with this reason without finding anything, which would have had connections with sabotage. It is in every case impossible to say, that it was not sabotage by 100 % probability.

   In my opinion the reason nr 1 (fall of the block) is the most probable reason.

THE UNDERGROUND AMMUNITION STORAGE (THE TUNNEL SYSTEMS)

The plan of the underground storage is to be seen in Fig 1. The underground storage was only a part of the whole Depot. On the ground there were many workshops, barracks and different kind of storages.

This Tunnel System was consisted of the (so called) main part, of tunnels 1-5 and of two separate Tunnels numbers 6 and 7. Each one had volyme of 2700 m3.

Tunnels 1-5 included mostly ammunition and gunpowder. In tunnel number 6 there was mostly gunpowder (about 220 tons) and in tunnel 7 mostly TNT and RDX (together 310 tons). There were also small storages numbers 8 and 9, including only some hundreds of kilos explosive material.

The hill where the tunnels were located was about 200 m x 350 m and was about 15-25 m above its surroundings.

The roof of the Tunnels varied from 15 to 22 m. The walls in the main part were 17 m each. The wall between number 5 and 6 was 32 m and the wall between 6 and 7 was 18 m.

THE EVENTS

The assumed series of events are about following:

First it happened something (fire, deflagration, detonations) in the tunnel number 5. The rising pressure in this tunnel opened primary joints in the rock. The Blast Wave carried materials (ammunition etc.) to the connection tunnel, to other tunnels and through cracks to the hill top.

The explosions in the main tunnels caused ignition of gunpowder in tunnel 6, that turned into a detonation. This lifted the rock masses above the tunnel and carried huge

blocks of the slope further down the side. The detonation continued to tunnel 7, the explosion of which caused a crater to form and a heavy rock shower. The block formation around the crater was heavy and fissures and faults followed the tectonic directions of the rock. A primary joint of the rock parallel with the directions of the tunnel 4, determined the movement of the rock masses and spared tunnels 1, 2, 3, and 8 from further structural damage. This joint, which was opened by the blasts in the main tunnels, served as a reflective surface for rock movements from the explosions and for detonation blows in tunnels 6 and 7.

The Investigation Committee had many good reasons to come to above mentioned conclusions of what happened in the Tunnels.

The best information of exact times of detonations was got from the observations of the INSTITUTE of SEISMOLOGY. According the seismologial report following happened. The first explosion occured at 5.25 o'clock in the morning. Its estimated TNT - equivalency was 4 tons. The second explosion happened 27,8 s later and its TNT - equivalency was 100 tons. Seismologists said that above mentioned amounts are not very exact, but their relation 1:25 is more certain.

Further they said, that before the first explosion they would have found explosions which were 1/10 part of the first explosion. Between above mantioned two explosions it would have been possible to find explosion as big as or bigger than the first one. None of these kinds were found. After the second explosion, possible smaller explosions would have been covered up by the second explosion in seismograms.

After above mentioned two explosions there were fire and single small deflagrations and detonations under one week's time in the Tunnels and in the surroundigs.

EFFECTS TO THE TUNNELS

Figure 2 shows the situation in the Tunnels after explosions. Tunnels 6 and 7 are wholly destroyed, there is only a crater. The deepest part of the crater is in the middle between the Tunnels. Figure 3 shows the ground profile before and after the explosion.

Tunnels 4 and 5 are only partly destroyed, the rears are damaged only a little.

Tunnels 1, 2 and 3 are in "good" condition, but they are not used any more. Pictures from the tunnel 1 and from the connection tunnel near tunnel number 1 show these being in rather good condition.

EFFECTS TO THE SUBROUNDINGS

The most dangerous effect to the surrounding was a shower of rock blocks and stones. Effects of the Blast wave and the earth vibration are very difficult to see apart from the effects of the rock shower.

In the pictures there are shown the effects of the rock shower to the buildings and surroundings. Specially in this accident the effects of flying stones, blocks and dust were typical effects to surroundings. For example there were hay and berries spoiled by dust in large areas (Fig. 5).

In Fig 4 there can be seen areas, where most of the flown blocks were found. Typically, they have been directed mostly southwest. Also very many windows were broken, the longist distance was 7 km. There were some astonishing features in the effects, for example a brick chimney is almost undamaged although it is near the opening of the Tunnel System.

Now , today there is the Depot of Finnish Defence Forces working at the same, area, where the catastrophe occured. However, there is now only a little amount explosives material in the Depot.

REFERENCES

The Official Report of the Uusikylä
Accident Investigation Committee 1966
(in Finnish)

Vähäsarja Pentti
THE EXPLOSION CATASTROPHE AND CHARACTERISTICS OF THE ROCK AT UUSIKYLÄ 1970
(in Finnish, Abstract in English)

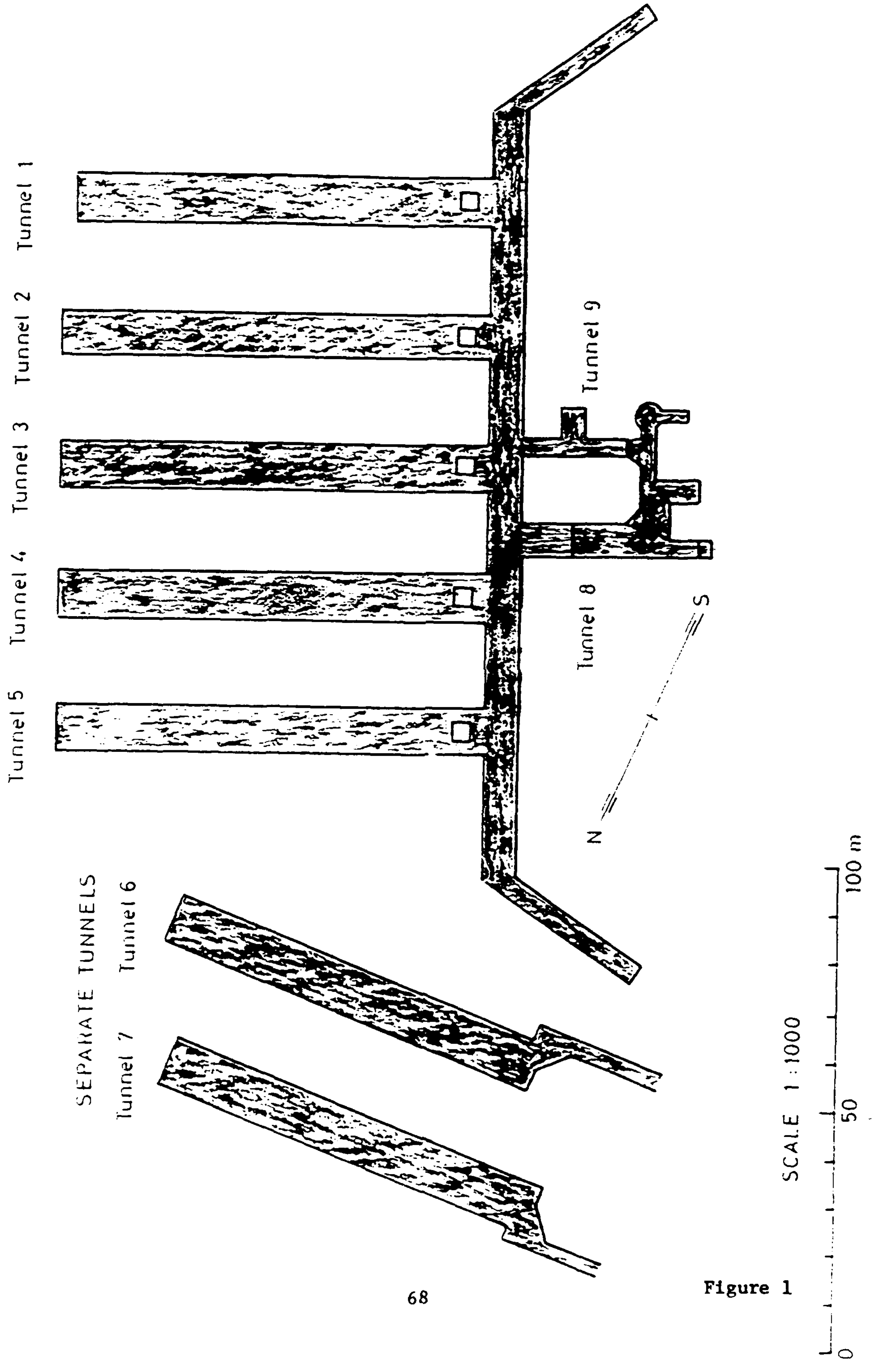

MAIN STORAGE TUNNELS
Tunnel 1
Tunnel 2
Tunnel 3
Tunnel 4
Tunnel 5
Tunnel 8
Tunnel 9
N
S
SEPARATE TUNNELS
Tunnel 6
Tunnel 7
SCALE 1 : 1000
0
50
100 m

Figure 1

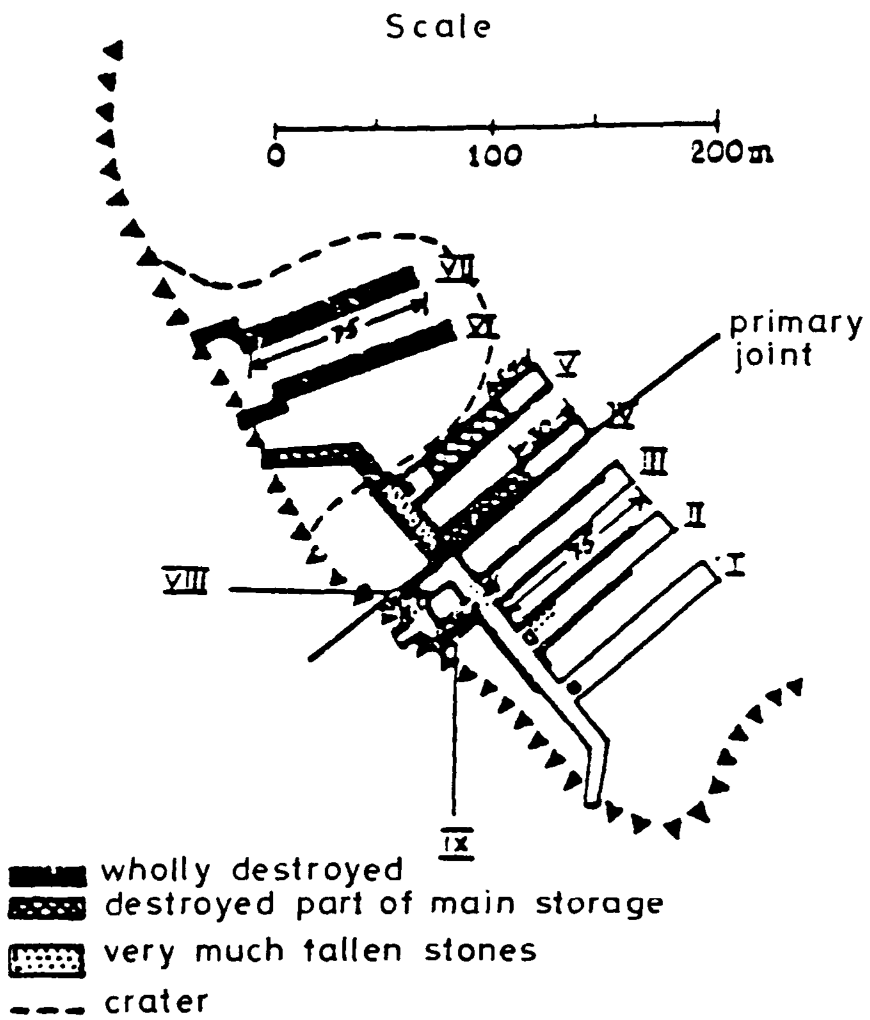
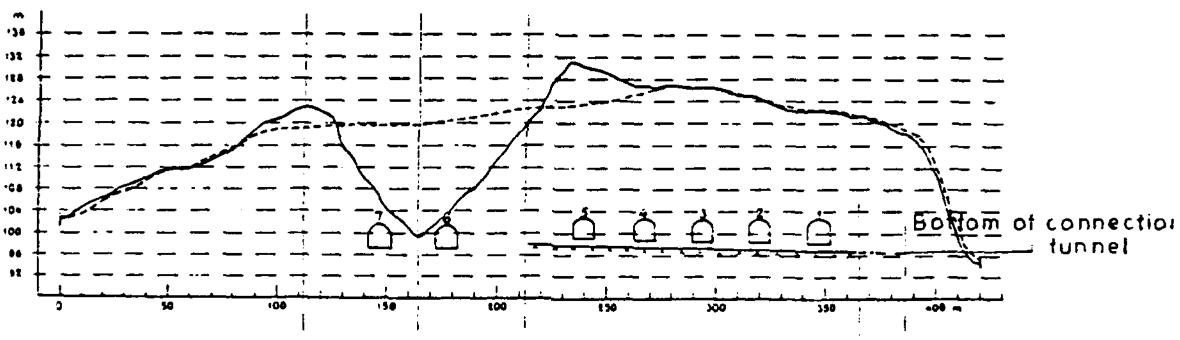

Scale
0
100
200m
VII
VI
V
IV
III
II
I
VIII
IX
75
primary joint
wholly destroyed
destroyed part of main storage
very much fallen stones
crater

Fig. 2



- - - - original ground surfice

——— ground surfice after explosion

Fig. 3

IN THE DETONATIONS FLOWN STONES

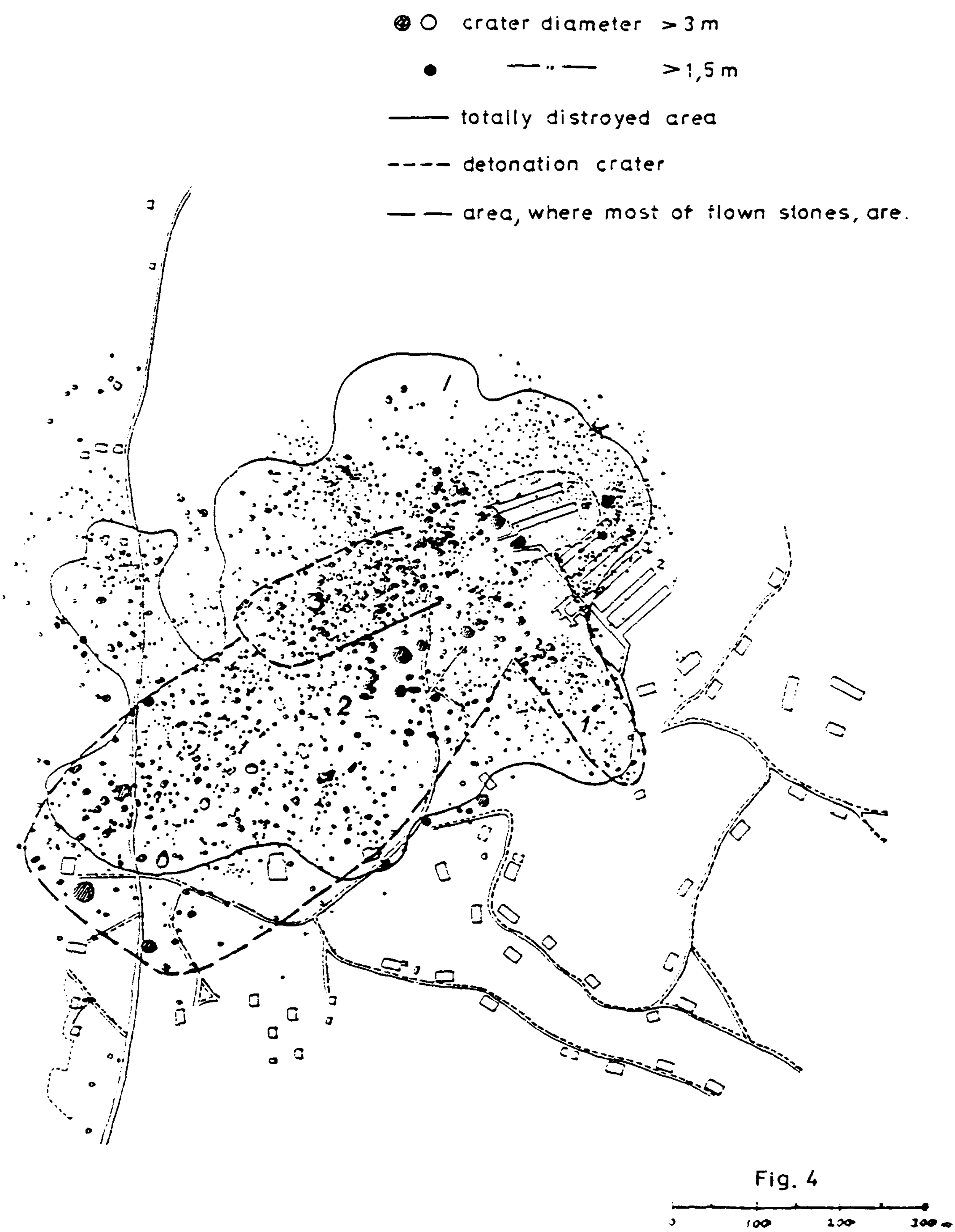
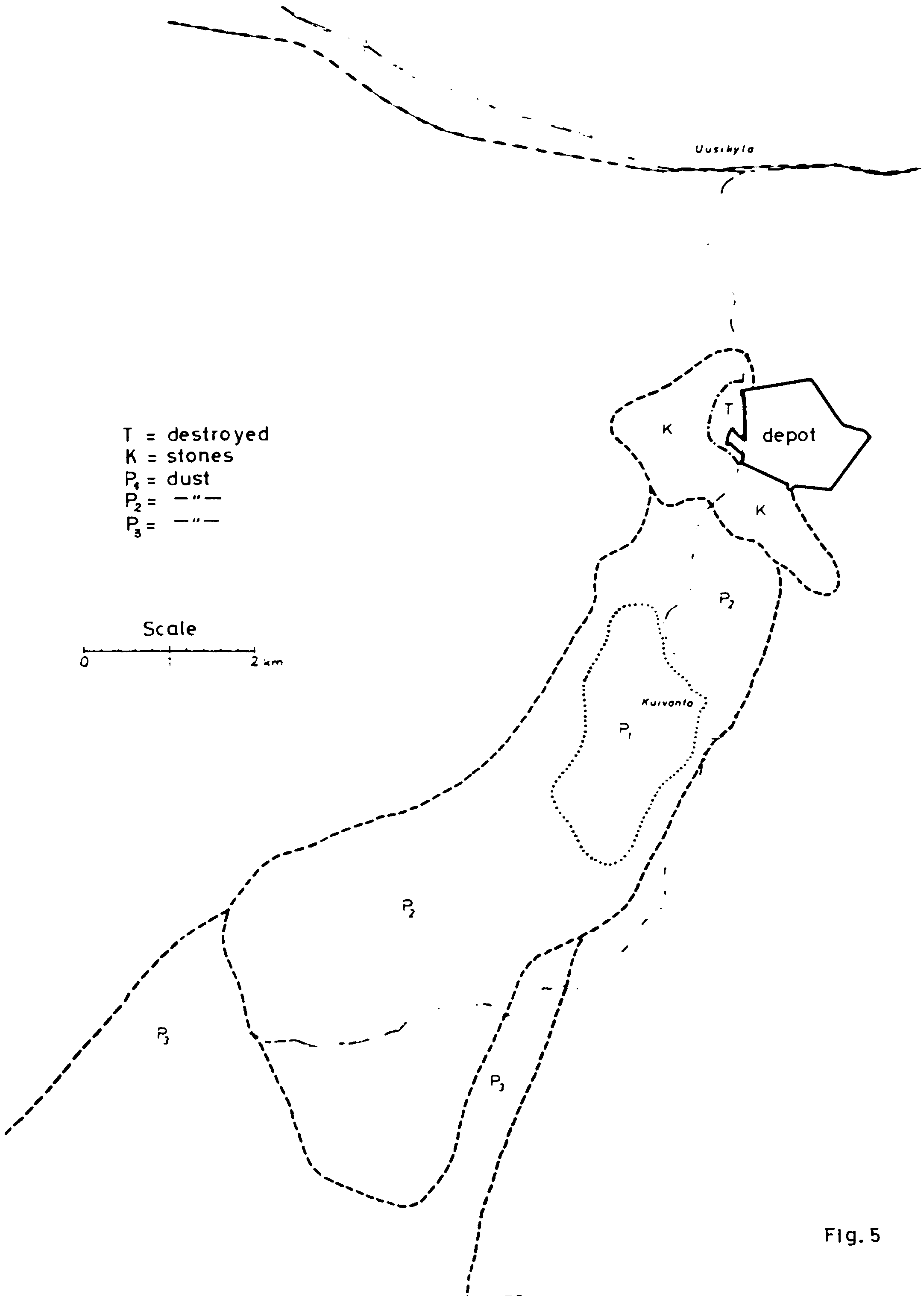


Fig. 4


Uusikyla
T = destroyed
K = stones
P1 = dust
P2 = —"—
P3 = —"—
Scale
0
2 km
depot
T
K
K
P2
Kuivanto
P1
P2
P3
P3
Fig. 5

PICTURE 1 Near the crater. Something is still burning.

PICTURE 2 When the pressure lifted the rock, the open cracks were filled by stored materials.

PICTURE 3 This Block's weight is about 1000 ton. It is on the blockwall.

PICTURE 4 Blocks of rock above the main part of Tunnels. The brick chimney is to be seen in the backgrounde. It is a little miracle, that it still is there.

PICTURE 5 The Tunnel 1.

PICTURE 6 This Block has flown about 750 m.

PICTURE 7 The Living house, 650 m from the Explosion.

PICTURE 8 This House was about 300 m from the Tunnels 6 and 7. One Person was in this House, he survived (badly injuried).

PICTURE 9 This Barrack situated 480 m from the Explosion.

MJU-8 IR FLARE MIX FIRE AT LONGHORN AAP, 28 SEPT 91

RALPH A. KNAPE

U.S. ARMY ARMAMENT
MUNITIONS AND CHEMICAL COMMAND

25th DEPARTMENT OF DEFENSE
EXPLOSIVES SAFETY SEMINAR
18-20 AUGUST 1992

ABSTRACT OF THE INCIDENT SUMMARY FOR LONGHORN AAP FLARE MIX FIRE

The incident is best characterized by noting that meeting compliance requirements is not sufficient to prevent accidents. In this case, a death and a serious injury resulted from an operation which was well analyzed and thought to be well protected.

The operation is explained to provide a basic understanding of the factors which came into play during the fire. Details on building layout and construction, the installed deluge system, operator location, hexane use and properties, bonding and grounding, and the hazard analysis effort are covered to demonstrate how individual factors were addressed. Significant interrelationships are identified to illustrate the failures involved in the fire.

Significant lessons learned are covered, concentrating on the solutions to the identified areas of failure. The most significant lesson is that regulatory compliance is only the first step toward accident prevention.

ACCIDENT SUMMARY

MJU-8 IR FLARE MIX FIRE AT LONGHORN ARMY AMMUNITION PLANT

28 SEPTEMBER 1991

On 28 September 1991, the U.S. Army Armament, Munitions and Chemical Command (AMCCOM) experienced a serious incident. The incident involved 187 pounds of MJU-8 IR flare mix in the production facility, building 54-H, at Longhorn Army Ammunition Plant (AAP). The seriousness of the incident can not be measured exclusively by the amount of damage to the facility, it was relatively minimal, or even in the serious personnel injuries, one man was severely burned and another subsequently died. A significant measure of the seriousness of this incident was the fact that virtually all compliance related requirements were met and the fire still occurred, and with serious results.

The MJU-8 flare mix involved in the incident is a mixture of magnesium, teflon and binder. During the mixing process, acetone is used as a solvent to promote mixing. Hexane is used at the end of mixing to drive off the acetone and promote precipitation of the mix solids. After precipitation of the mix, the hexane is dumped off the mix in an open pan and allowed to run into a collection bowl. Following hexane collection, the collector bowl is moved from the end of the dump pan and the mix is dumped into the open pan for further processing. The fire occurred when the hexane dumping was just being completed and the bay was about to be prepared for mix dumping. The operator who would be entering the bay was already making sure his aluminized suit was on properly in preparation to enter.

(See Diagram 1.)

Diagram 1 cross-sections the mixing bowl in upright and dump positions. In the first case, the MJU-8 mix is shown covered by a layer of hexane liquid as the mix precipitates out in the absence of agitation. The second illustration shows the mixing bowl as pouring off of hexane liquid is completed. (Actually, the liquid is about 93 percent hexane and 7 percent acetone at the time of dumping.) The second illustration shows the mixing bowl in the position it was in at the time of the incident. The fact that the side of the bowl is turned about five or ten degrees past horizontal is significant.

The dump operation was conducted remotely. The operator at the dump controls watched the operation through a lexan window. Operations were viewed indirectly in a mirror. No personnel were allowed into the dump bay or allowed to pass in front of the dump

bay opening during actual dump operations. Access was restricted by operating procedures and controlled by the use of rope barriers on either side of the bay. Personnel in protective aluminized suits brought the mixing bowl full of mix into the bay. Personnel in aluminized suits later entered between the liquid and the mix dumps to prepare the equipment for mix dumping and after the mix dump entered to containerize the mix.

Investigation after the incident located the point of ignition of the fire as the area of hexane dumping and collection and tracked the path of the fire as it spread. The path and speed of fire spread during the incident was determined by a number of factors, including the presence of hexane vapor, the type and amount of mix in the bowl, the building construction and wind direction. Diagram 2 shows the path of the fire and indicates the location of the personnel in the building at the time of the fire. Evidence in the building indicted that the expanding fireball carried particles of burning mix as it bounced off the dump bay wall and swept out into other building areas. Size of the arrows is used to denote the relative amount of flame and heat as the fireball expanded.

(See Diagram 2.)

Personnel at locations one through three were near exits and exited immediately as the fire initiated in the dumping bay, before the fireball could spread completely into the control room. Personnel at locations four and five were not in positions to immediately exit and had to fight their way through the fireball and burning mix in the control bay to exit. Both were severely burned and one subsequently died.

The Board of Investigation (BOI) into the incident revealed that there were multiple factors which contributed to the incident and the resulting injuries. The overriding factor which became obvious as the investigation proceeded was that simple compliance with regulatory requirements is not sufficient to provide the safety environment which is required. Thoughtful consideration of all factors and the way each combines with all the others is required for effective safety.

(See Chart 1.)

Chart 1 summarizes the major causes and factors contributing to the severity of the fire. Because of the relationships between the various factors, some factors will come into the discussion more than once. It is important to understand that the BOI found the accident to be the result not of a single factor but of a combination of all the factors.

Building 54-H was modified in 1987 to provide a production facility for MJU-8 IR flare mix. Very few structural changes were made to prepare the building for IR flare production. In terms of this incident, the single most significant change was dividing Bay 108 into Bays 108 and 108A by the installation of a steel barricade wall floor to ceiling. This barricade installation divided the process of preparing components for flare mix from the dumping operations. Other noteworthy modifications included providing two sliding doors to separate the mixing bays from the control room. The second of these doors was provided after an previous incident where fire in a mixing bay partially vented around the single door.

The mixing area was recognized as a severe hazard to personnel in case of a fire because of the energy added during mixing and confinement by the mixing apparatus. The dumping bay was evaluated as much less hazardous because of the lack of energy input into the bay operations. Limited local testing of the mix demonstrated that hexane wet mix in an upright bowl with deluge coverage burned without significant energy. This testing lead to the conclusion that significant hazards existed only in the mixing bay. Based on this, sliding doors used to isolate the mixing bay were not perceived as necessary for the dump bay. Similarly, the presence of the hexane and the lack of any apparent energy source did not cause concern in transporting the mixing bowl through the control room in its passage from mixing to dumping.

During the evaluation and modification of Building 54-H, the subject of frangible construction was raised as a result of the risk analysis efforts. Because of the recognized hazard potential, frangible construction was recommended for the ramp wall area immediately in front of the dump bay. The recommendation was directed to the local engineering staff, who reviewed the building construction and found the existing wall to be "frangible". On this basis the existing wall was used unmodified.

The original design of the wall was to be frangible for high explosives. The MJU-8 IR flare mix dumped in the bay has many of the properties of mass fire producing material, especially when saturated with hexane, as at this point in the production process. As demonstrated in the subsequent incident, MJU-8 mix wet with hexane creates overpressures so low that the transite on two by four construction of the building was unaffected during an incident. The regulatory requirement for hazard analysis was met but the recommended construction provided no venting in the incident. The transite construction, instead, helped direct the

fireball into the area occupied by personnel. Either modifying the wall construction to make it weaker or closing off the opening to the control bay would have provided better personnel protection and prevented the fire damage to the control bay.

One of the first questions asked by the BOI was "Why did this fire get out of hand if an ultra high speed deluge system was in place?" The investigation revealed that a system was in place that met all requirements for response time and testing. However, detector and nozzle positioning was not sufficient to catch the fire during ignition or confine it once the mix was burning. Design and testing was based on an upright bowl at the time of ignition, locating deluge heads almost directly over the bowl position. As previously noted, at the time of the incident the bowl was rotated 95 to 100 degrees from the upright position. The ultra high speed deluge functioned within design parameters once it saw the fire, but the water fell ineffectually on the side of the bowl, unable to attack the mass of burning mix. The mix burned completely in the bowl leaving only a minimal amount of ash. Substantial amounts of ash accumulated on the floor of the dump bay in the area covered by the deluge heads indicating the controlling effect of the deluge when the water could reach the burning mix.

The design of deluge systems must provide coverage for all operations without obstruction for either detectors or water nozzles. Simple compliance with regulatory requirements does not protect operations, the carefully engineered and managed system can. The BOI felt that the properly designed and placed deluge system could have substantially reduced the effect of the incident.

Questions were raised about the requirement for the personnel protective equipment. The injuries occurred in a control room which was considered a safe area and where aluminized protective suits were not required. When operators entered the mixing or dumping bays, they were wearing protective suits and hoods as required by the operating procedure. The lack of isolation of the dump bay by construction of barricades or walls allowed the exposure to the burning mix.

Another operator protection issue is operator location and egress. In this case, the control operator and quality inspector were located where, in the event of an incident in or coming into the control room, rapid egress was not possible. In this incident, three of the personnel in the bay, the two mix operators and the bay leader, were required by their duties to be

near doors and these three people escaped unharmed except for minor first aid injuries. The egress route of the dump operator and quality inspector was longer and was hampered by a large ventilation fan blocking the nearest exit. Blinded by the heavy smoke, both of the burned individuals attempted egress through that exit before finding alternate egress routes. The blocking of an egress route was one of the few regulatory violations found during the BOI.

A major factor in the incident was the fire hazard presented by the hexane used to precipitate the mix. Although systems were in place to collect hexane vapors in the dump bay, and to detect potentially dangerous concentrations of hexane vapors in the bay, the fire most likely initiated at the top of the hexane collection bowl.

The lower explosive limit of hexane is 1.2 percent and the upper explosive limit is 7.5 percent. The vapor density is 3.0 with a flash point of -7 degrees Fahrenheit. This means that hexane readily creates a easily ignitable concentration which collects in low areas and on top of surfaces. These features combine with the fact that flowing hexane generates and holds a static charge of about 50 static volts to create a very hazardous situation during production operations.

All permanently installed equipment in the dump bay had been bonded and grounded, and had undergone periodic testing. However, the BOI identified a screen that the hexane flowed through which was electrically isolated due to the addition of a nonconductive rubber gasket. The circular metal screen had not been tested when other equipment was tested. It was determined by the BOI that, most likely, a static spark from the screen ignited the surrounding hexane vapor which in turn ignited the MJU-8 mix.

(See Diagram 3.)

The conclusion reached by the BOI was that the static spark was the root cause in the incident. The day that the incident occurred was the first very low humidity, low temperature day since adding the rubber gasket to the screen, creating a high static environment. A new dump operator, less experienced at the dumping operation was at the controls, possibly causing less smooth flow of hexane compared to operators more practiced at dumping, raising the potential for static generation and discharge. These factors combined to provide the opportunity for the spark. Testing after the incident proved that the dump pan above the screen and the collection bowl below the screen were

grounded, so two possible directions existed for the spark to jump. Both possible locations were known to contain hexane vapor even though both were covered by ventilation systems. A direct trail of hexane/hexane vapor led from the collection bowl through the area of the screen and to the mix in the dumping bowl. The entire hexane collection system quickly became involved and immediately ignited the mix in the mix bowl. Once ignited, the mix burned violently, blowing particles of mix out of the bowl, through the dump bay and into the hallway where those burning particles could be pushed by gas pressure into the control bay to surround the two operators.

The incident was not caused by gross regulatory violations, but was the result of the combination of many small problems which united to produce, sustain, and spread the fire. The root cause which allowed the minor problems to accumulate to the critical level was the failure to recognize and fully analyze hazards which existed and grew in a symbiotic relationship within the dynamic production process. The lack of recognition of the significance of details and process changes allowed substantial differences to exist between the hazard analysis and the overall process at the time of the incident. Specifically, errors in frangible building construction, safe separation from hazards, the deluge system, operator egress, and the failure to bond the screen to the existing grounding system were all failures in the system which went unrecognized individually. Without constant monitoring of the operational processes such hazard analysis failures will contribute to accidents.

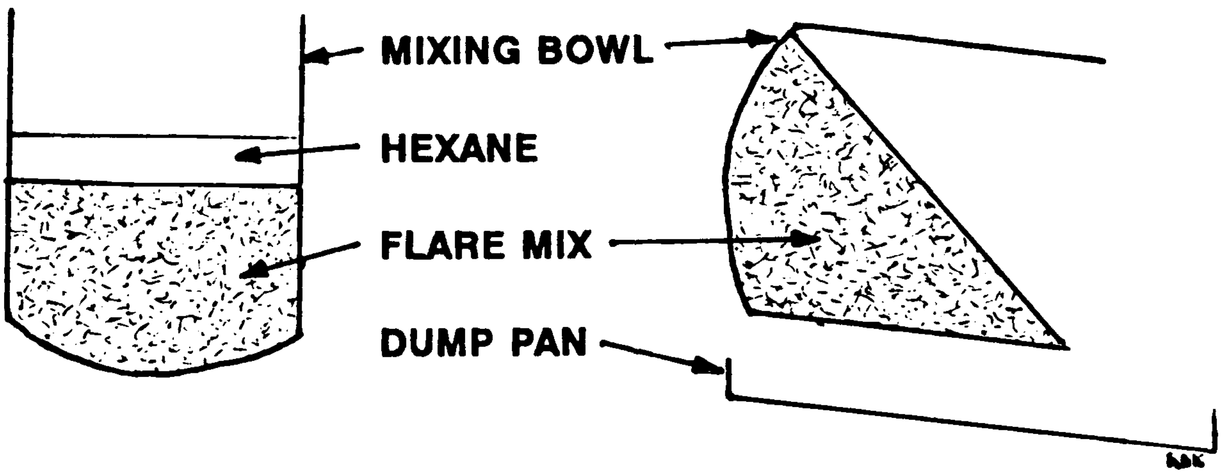
(See Chart 2.)

Each accident is a learning experience. The items listed in chart 2 briefly cover the major lessons learned as a result of this incident. Proper building configuration would have prevented the spread of the fire to the control room area, frangible construction and isolation of hazardous operations being the applicable criteria. Testing completed before the fire demonstrated that the deluge system configuration in use was capable of controlling a mix fire in the bowl, but systems must be designed to cover all operations or fire control is lost as it was in this incident. Operators must be located so as to provide not only protection from incidents but also clear egress if the provided protection fails. This incident was at least partially caused by a failure to understand the properties of MJU-8 flare mix during the production process and the hazards involved with using hexane. Although local procedures very carefully applied the requirements for bonding and grounding equipment in the operation, the screen which helped generate the spark went

ungrounded because it was considered as exempt portable equipment. Careful analysis of the total system could have revealed the individual minor weaknesses and probably greatly reduced or even eliminated the incident. The real lesson learned is that regulatory compliance is only the first step toward accident prevention. Careful analysis of the relationship between all factors is required for true accident prevention.

DIAGRAM 1

MIXING BOWL AND MIX



UPRIGHT POSITION

HEXANE DUMP POSITION

DIAGRAM 2

BUILDING 54-H, NORTH END
PATH OF FIRE

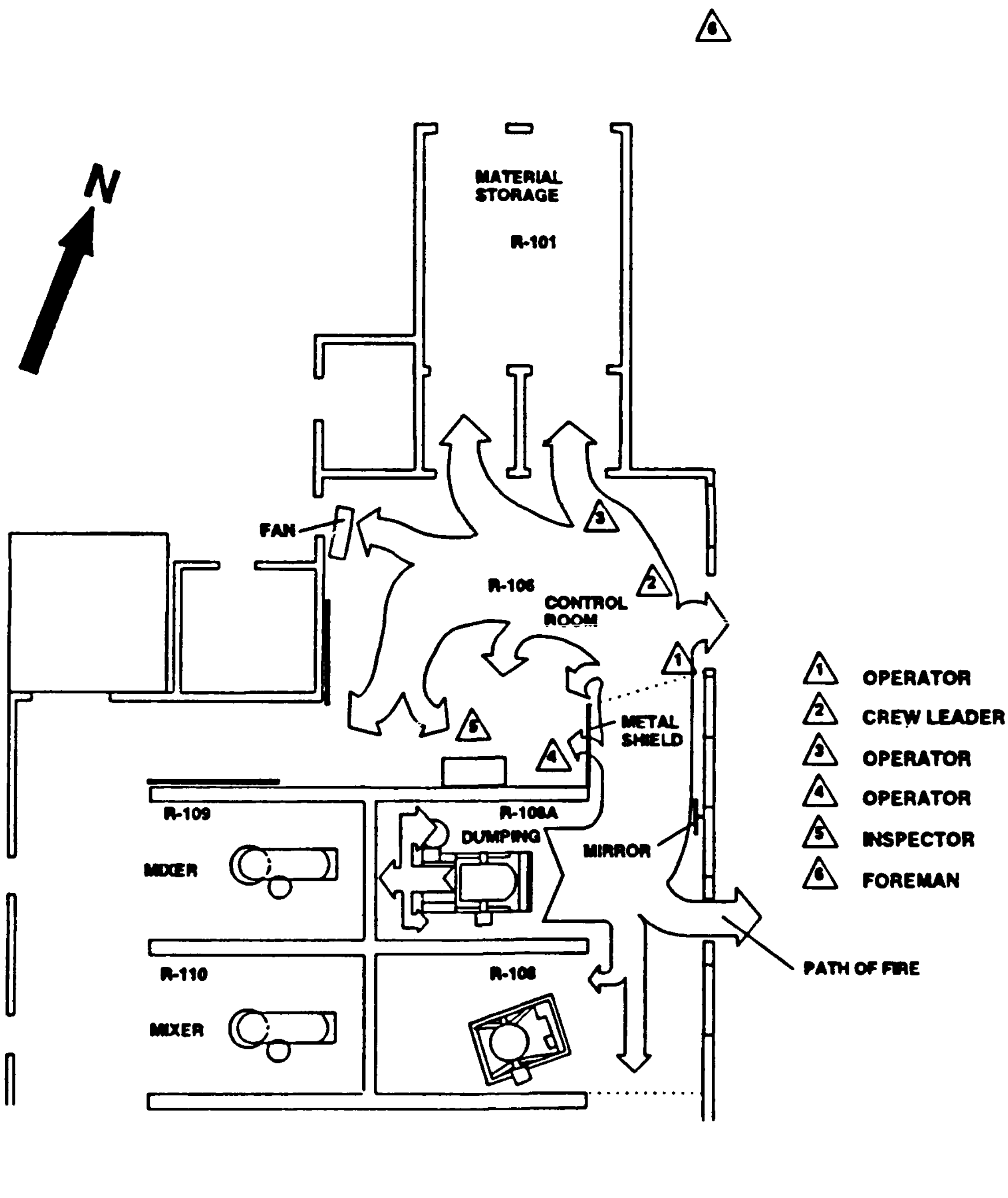


CHART 1

FACTORS INVOLVED IN THE FIRE

BUILDING CONSTRUCTION

DELUGE SYSTEM

OPERATOR PROTECTION

HEXANE

GROUNDING/BONDING

HAZARD ANALYSIS

DIAGRAM 3

DUMP PAN AND HEXANE COLLECTION BOWL

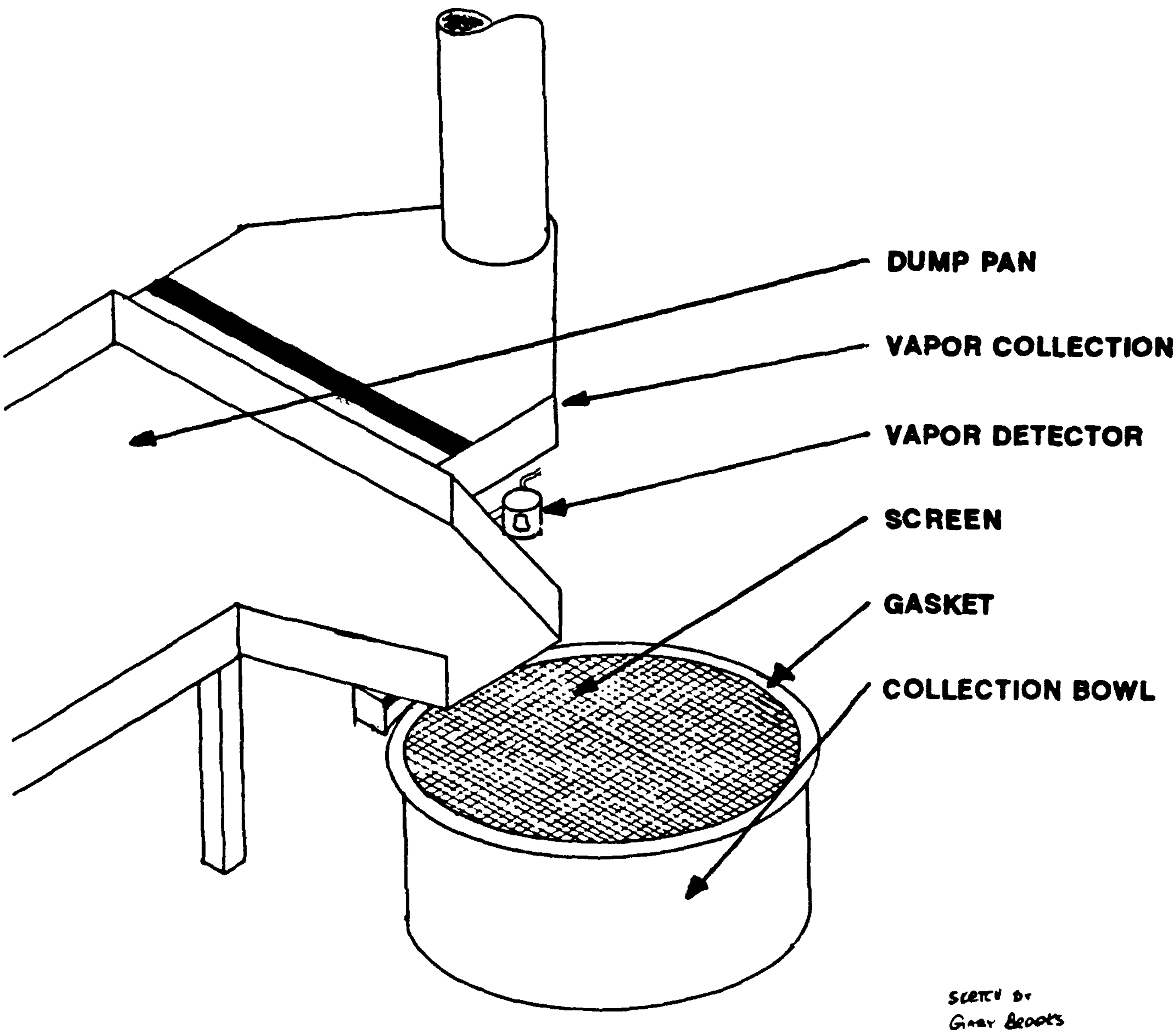


CHART 2

SIGNIFICANT LESSONS LEARNED

- PROPER BUILDING CONFIGURATION WILL PREVENT FIRE SPREAD.

- DELUGE PROTECTION MUST COVER ALL STEPS OF THE OPERATION.

- PROPER OPERATOR LOCATION AND PROTECTION ARE REQUIRED.

- UNDERSTAND THE MATERIALS IN USE.

- CAREFUL BONDING/GROUNDING OF ALL EQUIPMENT IS NEEDED.

- PROPER ANALYSIS OF THE HAZARDS IS CRITICAL.

THE EXPLOSION OF THE DISPLAY FIREWORKS ASSEMBLY PLANT "MS VUURWERK" ON FEBRUARY 14, CULEMBORG, THE NETHERLANDS

25th DoD Explosives Safety Seminar
18-20 August 1992, Anaheim, California

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1 INTRODUCTION

On February 14 1991, a heavy explosion completely destroyed the assembly plant for display fireworks 'MS Vuurwerk' in Culemborg, the Netherlands.
An investigation was carried out in order to determine the strength of the explosion on the basis of damage caused to the buildings in the vicinity.
Furthermore an investigation was carried out of the crater and its direct vicinity to find the cause of the explosion.

Results of the investigations performed by the TNO Prins Maurits Laboratory were presented in a report (in Dutch): 'Report from the Prins Maurits Laboratory TNO concerning the explosion of the 'MS Vuurwerk' assembly plant for display fireworks at Culemborg on Thursday 14 February 1991.
This paper gives a summary of that report.

2 LOCATION

The assembly plant for fireworks 'MS Vuurwerk' is situated 5 km outside the built-up area of the town of Culemborg in south-west-west direction. Culemborg itself is situated about 15 km south of the city of Utrecht in the centre of the Netherlands. Heart of the plant was a bunker from World War II. This bunker is situated at the foot of a dike which was part of the 18th century water defense system of Holland. The dike starts at the river 'Lek' and passes the plant in south-south-west direction (see Figure 1A).

The plant is situated at a distance of 50 m from the dike. A number of houses and farms are situated against the other side of the dike. The dike itself has a height of 5.8 m. At the plant side of the dike, only a couple farms are present, the nearest building at a distance of about 200 m.
The landscape is very flat and open. The dike is the only elevation present (see Figure 1B).

Figure 1A Culemborg and surroundings

Figure 1B The location of the assembly plant

Two buildings were present on the premises (see Figure 2).

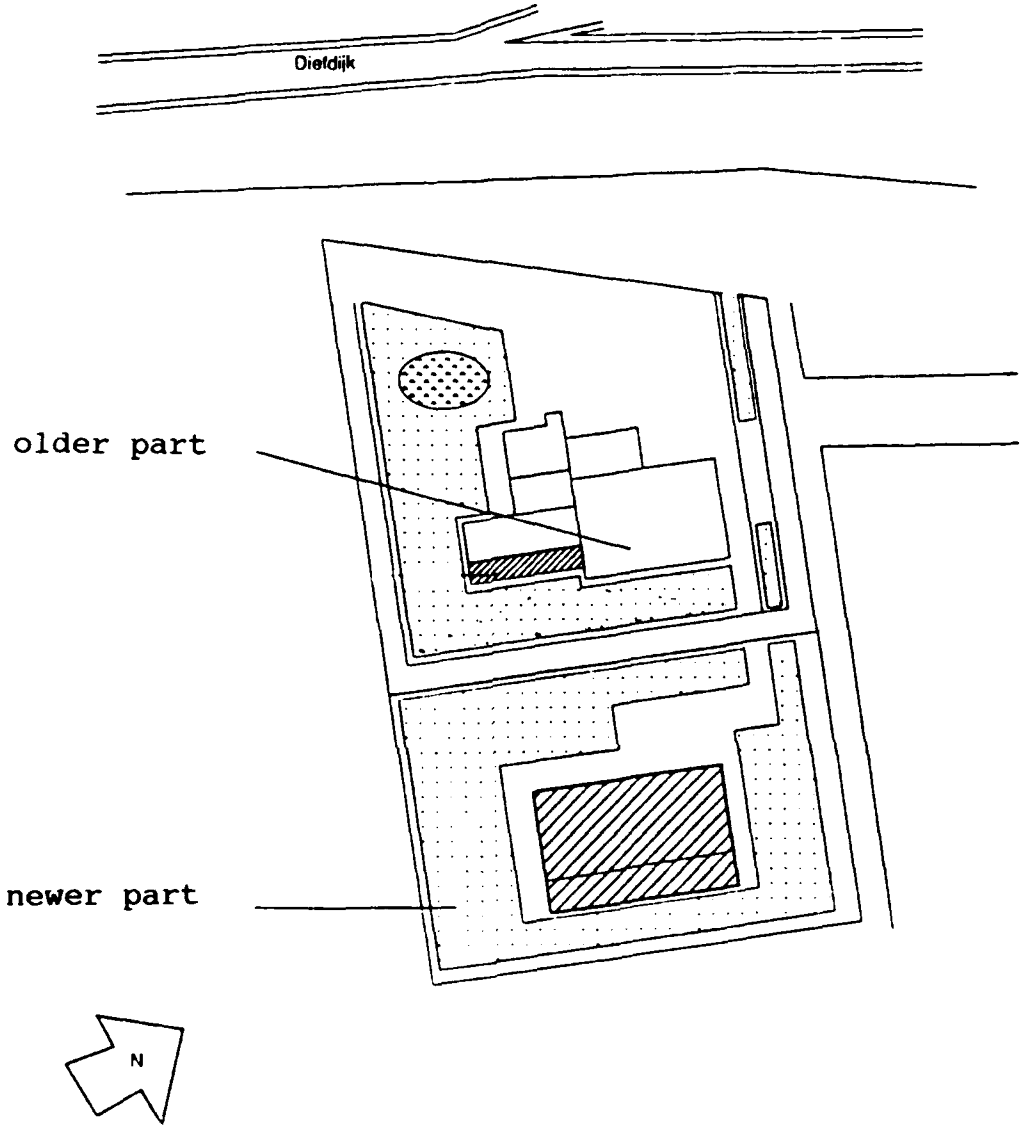

Figure 2 Lay out of the assembly plant

The first one consisted of the old bunker, an administration office, an assembling hall of 25 by 16 square meters and 5 small storage rooms. The other building 20 m east of the first one was built in 1990 and in service since a couple of months. It consisted of an assembling hall of 20 by 12 square meters, four storage rooms and two workrooms (see Figure 3). Figure 4 shows a section of the building. The walls of the storage rooms were made of 0.2 m thick unreinforced concrete blocks while the ceiling was made of concrete hollow core slabs. The inner wall of the cavity walls were also concrete blocks while the outer

wall was masonry. The assembly hall was composed of steel trusses covered with asbestos plates.

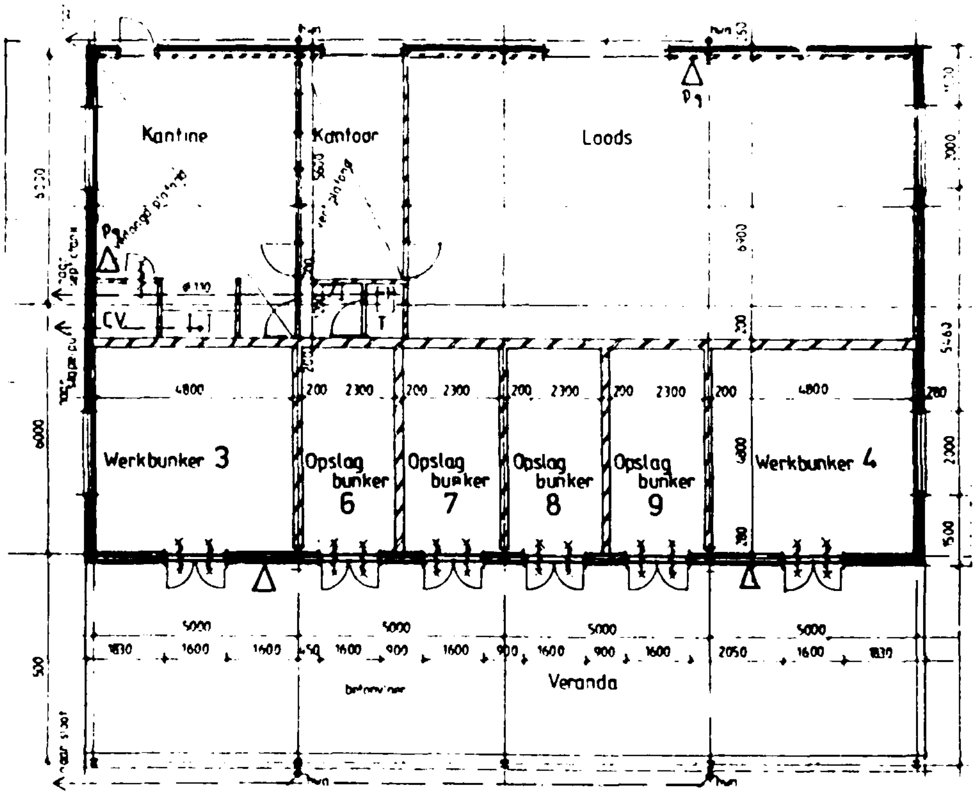

Figure 3 Lay out of the exploded building

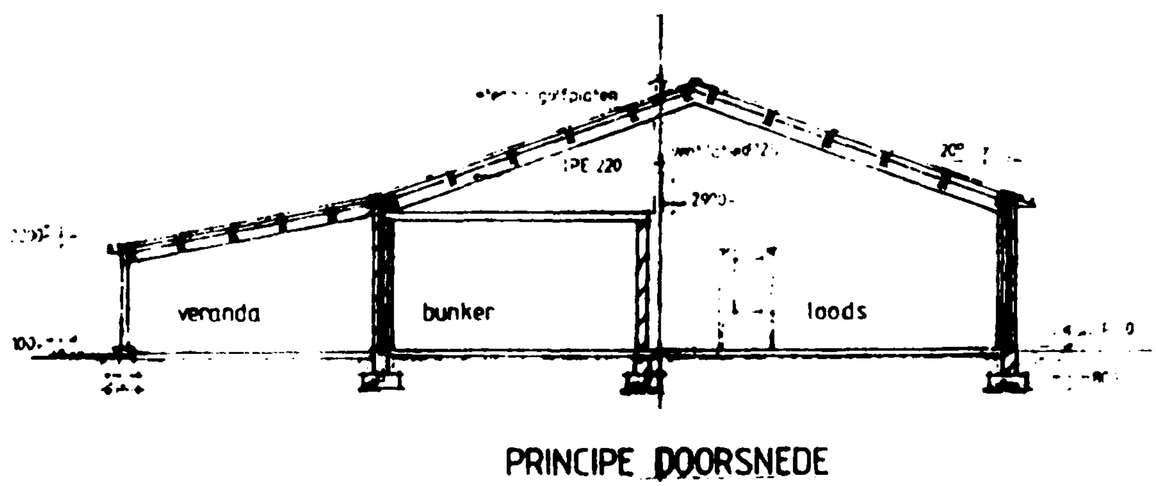

Figure 4 Section of the building before the explosion

3 THE EXPLOSION

At about 11.50 hours in the morning of 14 February a big bang was heard by the farmers and the inhabitants of the town Culemborg. Initially it was thought that something like an aeroplane had crashed. Although it was not confirmed by all witnesses and therefore not generally accepted, a second much stronger explosion occurred within 20 seconds. As pieces of concrete and wood started to fall from the sky, people realised that the explosion occurred within the fireworks plant.

It appeared that the new building was completely vanished and that only a large crater was left. The crater dimensions where 10 by 5 meters with a depth of more than two meters (see Figure 5).

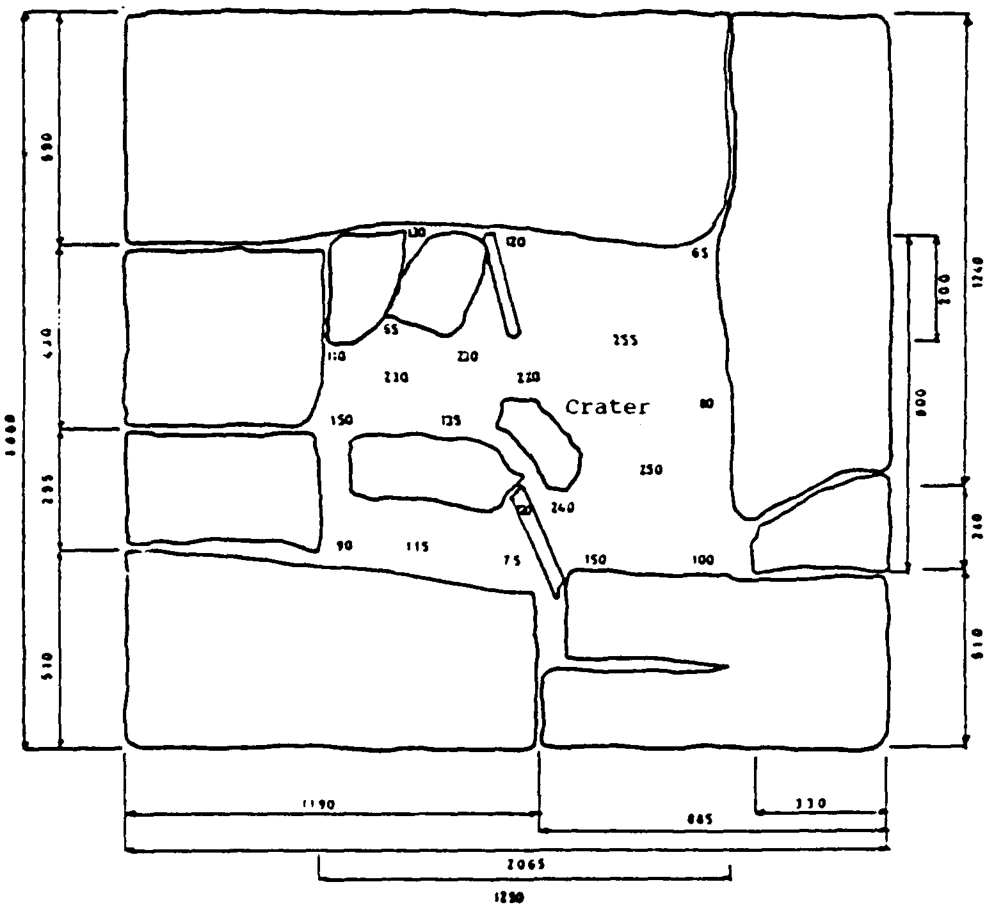

Figure 5 Overview of the crater

The old building was set on fire and minor explosions occurred during the rest of the day in the storage area where firework articles were ignited.

4 DAMAGE

Only a brief overview of the damage can be given here. One of the annexes to the report [1] gives an extended overview.
The nearest buildings were situated directly behind the dike. Although no house was collapsed, there was a lot of damage: roofs were pushed in and walls were heavily cracked. Most of the window panes were broken. Window and door frames were broken. Corrugated panels of barns were pushed in.
Up to 500 m behind the dike window pane breakage was observed.

The same pattern was visible on the eastern side of the dike:
At 500 m large wooden doors of 3 by 4 meters were lifted and pushed in. Most of the masonry of the houses within 900 m were found to be cracked.
At 900 m some frames of the double window panes were pushed in, roofs of large barns were lifted and wooden trusses were cracked.

Beside damage caused by the blast there was considerable damage caused by flying debris. The largest range over which debris was thrown was found on the eastern side. The storage rooms were situated on the eastern side of the assembling hall.
Up to 650 m east of the plant large pieces of concrete weighting 10 to 20 kg and parts of steel girders (length approx. 4m) were found.
Table 1 gives an overview of the large steel girders that were found and Figure 6 gives the location of these pieces of steel. All IPE's box girders and steel strips were parts of the steel truss of the exploded building.

Table 1: Overview of large steel girder parts found in the vicinity (location numbers refer to Figure 6)

Location	Type
1	I-beam IPE 180 length 4 m
2	box girder 5.5 x 5.5 cm^2 length 3 m
4	I-beam IPE 160 length 3.5 m
5	box girder 5.5 x 5.5 cm^2
8	IPE 180, 4 m
9	IPE 180, 4 m
10/11	box girder 5.5 x 5.5 cm^2 with steel strip 8x0.5 cm^2
12	strip length 1.5 m
13	IPE 180, 4 m
14	strip
15	steel cylinder, length 0.88 m, diameter 0.32 m
16	IPE 160, 4 m
17	strip
18	IPE 180, 4 m
19	box girder, 2 m

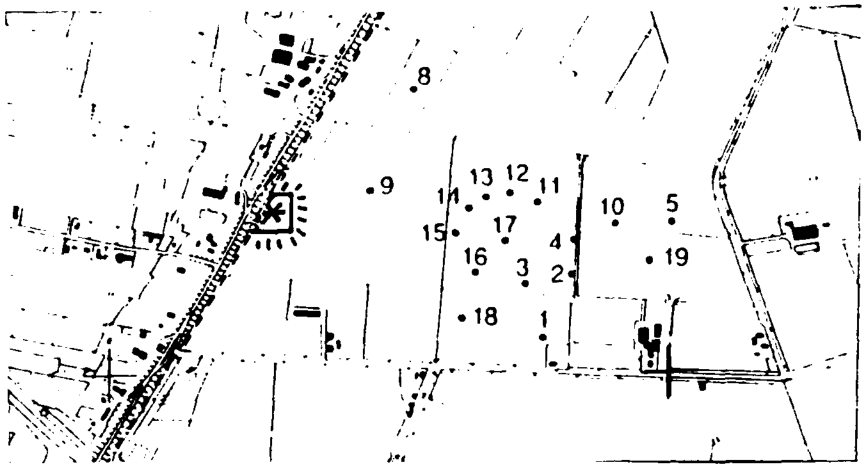

Figure 6 Location of the large steel girder parts

Most of the debris consisted of bricks or parts of bricks and concrete pieces with dimensions comparable to bricks. At a distance of 300 to 550 m in eastern direction, the distance between the pieces of debris was about 50 m.

To get an overview of the debris distribution around the explosion centre the near vicinity was divided in square sections of about 10 by 10 square meters (see Figure 7).

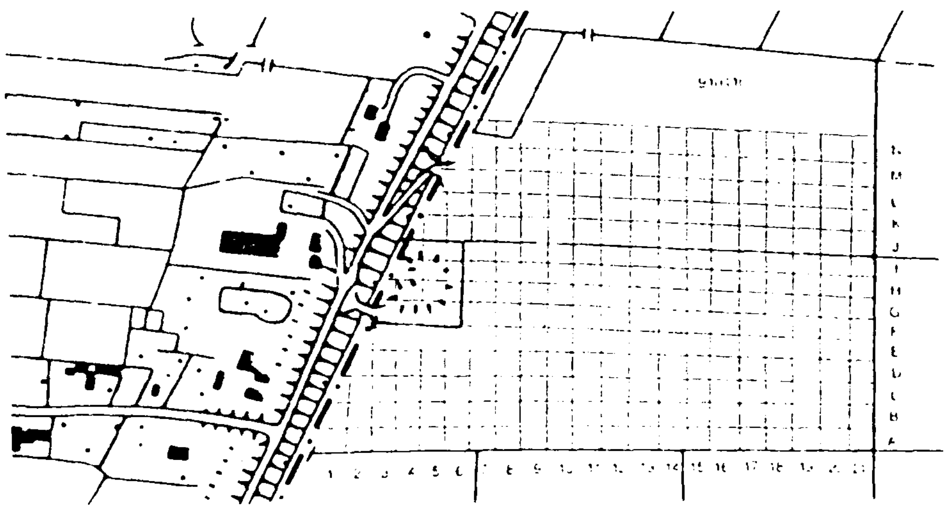

Figure 7 Sections for fragment and debris recovery

Each section was searched by a team of police and army men and every piece of debris weighting over 0.5 kg was gathered. Table 2 gives the total weight of the debris found in each section.

Table 2: Total weight (kg) of debris per section

row	section													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	143	0	43	183	215	175	0	0	0	0	0	0	0	0
2	147	165	175	104	45	177	0	0	0	0	0	0	0	0
3	70	146	158	238	99	1220	0	0	0	0	16	0	0	0
4	57	302	172	70	0	1550	0	0	0	0	0	0	0	0
5	48	175	239	230	995	1816	0	0	0	243	0	14	0	0
6	199	321	393	475	543	674	0	0	0	83	80	48	51	47
7	28	119	125	144	0	124	129	0	0	165	21	27	68	14
8	99	78	95	118	87	94	66	80	82	102	20	23	62	0
9	150	113	116	92	44	46	19	121	87	175	212	64	25	0
10	93	54	47	25	61	50	50	61	95	63	74	145	74	0
11	66	37	51	83	55	55	0	105	58	88	65	54	41	0
12	39	25	26	33	20	72	113	109	164	0	35	84	27	0
13	38	17	17	43	0	58	249	148	133	104	55	42	16	13
14	26	9	20	27	31	0	245	149	100	125	26	23	17	0
15	17	30	7	22	113	621	120	177	85	40	38	14	20	0
16	31	22	39	25	14	13	144	19	87	44	42	151	30	0
17	33	42	42	45	34	71	29	34	324	31	20	26	34	0
18	24	7	26	12	11	39	8	8	14	44	51	36	60	0
19	22	36	25	31	15	12	77	35	20	81	40	17	22	0
20	50	38	32	18	20	12	40	35	21	32	14	12	0	0
21	37	63	36	21	16	1	121	8	18	4	55	8	9	0

There was also considerable damage within the town of Culemborg itself. Large window panes were broken and chimneys were damaged. Roofs of showrooms were lifted causing damage to ceilings and goods stored inside.
It was reported that some minutes after the explosion a window pane at a location 50 km away broke due to a strong wind gust. The explosion was observed by seismological instruments more than 100 km away.

The estimate of insurance companies on the total costs of the damage was 50 million Dutch guilders so about 30 million US dollars.

5 EXPLOSION STRENGTH

Initially it was tried to estimate the strength of the explosion by the amount of damage of the buildings in the vicinity. It was however very difficult to distinguish zones with different levels of damage. Therefore two other approaches were applied.

First an estimate was based on window pane breakage. Based on the number of broken panes at certain distances and the dimensions of the panes and orientation with respect to the explosion, a rather accurate estimate could be made of the shock wave pressures at certain distances [2,3]. Applying the relation of overpressure versus distance for free field surface explosions gave un upper limit of 5000 kg TNT and a lower limit of 1000 kg TNT with a best average value of 2000 kg TNT.
The second approach was to compare the debris patterns and the crater dimensions with data from literature. For this data from the phases two and three of the joint Australian/UK fragmentation trials were applied [4]. These trials were performed with amounts of 500, 1800 and 5600 kg of explosives in structures very comparable to the ones present in the firework assembly plant. Although the comparison of data was very rough because of different ways of gathering and presenting data, it appeared that the debris pattern and crater dimensions of the 1800 kg trials matched best with those from the accident.

6 STORED QUANTITIES AND CLASSES OF FIREWORKS

Maximum quantities and types of fireworks to be stored in the plant are described in the Nuisance Act for the plant. This Act allowed the storage of Hazard Division (HD) 1.3 and HD 1.4 articles only. HD 1.1 and HD 1.2 articles were explicitly excluded with the single exception of 200 kg black powder, HD 1.1, to be stored in the World War II concrete bunker only.

An amount of 1000 kg gross fireworks was allowed to be stored in each of the four storage rooms of the exploded building. This weight is without the weight of the packaging material like wooden boxes. The fireworks should be stored within the transportation packaging. A maximum amount of 200 kg gross was allowed in each of the two workrooms.
The total allowed amount in the building that exploded was therefore 4400 kg gross which roughly implies an amount 1500 to 2000 kg explosive substances.
From data presented by the Ministry of Transport it could be concluded that 8000 to 10000 kg of fireworks were present in the plant, that is including the storage in the old building of the plant. This total amount of firework articles is about the maximal amount permitted by the Nuisance Act to be present at the plant

Based on the quantities present at the moment of the explosion and the estimated explosion strength it was concluded that a mass explosion occurred of the total quantity of fireworks present in the new building.
As only HD 1.3 articles were allowed to be stored this explosion effect was not expected at all. The outside quantity distances

were based on HD 1.3 distances and were not sufficiently large to protect against a mass explosion. Beside the need to find the cause of the explosion it was therefore very important to find the cause of the mass explosion of the storage of HD 1.3 articles.

7 INVESTIGATION TO THE CAUSE OF THE EXPLOSION

The investigation into the cause of the explosion was carried out in the direct surroundings within a radius of about 20 meters of the crater.
The investigation was focussed on:
- display firework articles or packages which probably do not belong to HD 1.3
- other explosive articles than display firework articles or packages which could be the cause of a mass explosion. For instance very fine grained black powder, special pyrotechnic mixtures or even high explosives
- packaging other than fibreboard or wood
- parts of the wooden doors of the storage rooms. This might give an indication whether a deflagration to detonation transition occurred.

The following types of display firework articles were found:

- Cardboard report shells

They had a diameter of five and eight cm. During the explosion the shells functioned properly. Some were found in the original state. A chemical analyse of the pyrotechnic mixture showed an aluminium/perchlorate mixture.
These pyrotechnic mixtures might give a mass explosion. This was demonstrated during trials performed in 1989 by TNO-PML as a mass explosion occurred during a bonfire test [5].

- Knätter vulcano

They had a height of about 25 cm and a ground diameter of 8 cm. They have all functioned properly. No vulcano was found in its original state.
These display firework articles showed no divergence of the HD 1.3.

- Silver Gerb from Le Maitre GB

Fragments of a pertinax like casing were found. The dimensions of the fragments were in the range of a few cm^2 up to a ten decade cm^2. These fragments indicate that the Gerbs did not functioned properly. The dimensions of the Gerbs casing were: diameter eight cm, length forty cm and thickness 0.6 cm. The weight of the explosive contents was about three kg and consisted of a mixture of black powder and titanium.

On May 14, 1991, bonfire experiments were carried out according to the UN test series 6C. The Gerbs however did not show a mass explosion. They ignited and functioned as they should

- Spheres made in Japan

The cardboard shells with a diameter of about eighteen cm were found in the original state. They were blown away and the shell was broken in two parts, due to the impact on the ground or due to the influence of moisture on the glued seam.
The explosive content consisted of black powder, saw dust and grains of seed.
These display firework articles showed no divergence of the HD 1.3.

- Roman Candles made in Russia

A few of them, about 5 %, were found totally intact, including the electrical ignitor. From the ruptured cardboard tubes it was concluded that most of the other 95 % were exploded. The wooden boxes, in which they were packed, were partially fragmented and splintered.

The materials which were found other than the firework articles or packaging were mainly building materials. An interesting material which was found were green plastic fragments of about a few cm^2. They belonged to a domestic wastes mini container. These fragments were also found underneath the concrete parts of the floor, in the direct surrounding of storage room 6.

The crater consisted of two parts, one part underneath storage room 6 and the other part underneath storage rooms 7, 8 and 9. The concrete floor plates of storage room 7 and 8 were partially shoved over the floor plates of storage room 6.
A reasonable explanation for this is that the explosion probably started in storage room 6, immediately followed by an explosion in storage room 7, 8 and 9. The latter was responsible for shoving the concrete floor plates over each other. This sequence of events is also in agreement with the locations where some of the green plastic fragments were found.

A second fact to support the theory of an initial explosion immediately followed by a second one, is the crack pattern in the concrete floor plates in front of the storage rooms (see Figure 8).

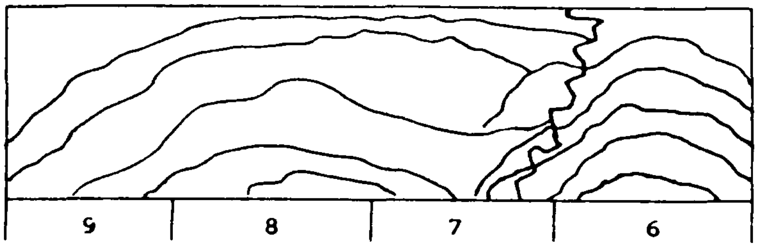

Figure 8 Cracks in concrete floor in front of the storage rooms

This pattern showed two circular crack zones, one in front of storage room 6 and one in front of the storage rooms 7, 8 and 9 and a large cross crack perpendicular to the storage rooms. The circular cracks in front of storage room 6 were not interrupted by the cross crack while the circular cracks in front of 7, 8 and 9 were. This indicates that the cracks in front of rooms 7, 8 and 9 were created after the formation of the cracks in front of room 6.

In summary:
- no display fireworks were found with a HD other than HD 1.3
- no articles or projectiles were found other than originating from the display fireworks or packages
- the domestic wastes mini container fragments and the crack pattern both indicate that there were two explosions, the second immediately occurring after the first one
- there was no deflagration preceding the detonation as no large parts of the wooden doors were found

8 CONCLUSIONS

It was concluded that:

- the damage caused by the explosion was comparable to a surface explosion of at least 1000 kg TNT. A best average value of the explosion strength is 2000 kg TNT
- the explosion started in one of the storage rooms of the new building which caused a sympathetic explosion in the three adjacent storage rooms
- the explosion could only by caused by an amount of explosives which acted as belonging to the HD 1.1

An amount of explosives with HD 1.3 can produce a mass explosion if:

- stored with a small amount of HD 1.1
- the classification of at least one type was wrong
- the storage conditions differed from transportation conditions
- assemblage of fireworks changes the nature of the article and thus influences the hazard division.

All these conditions could be present:

- although the presence of 200 kg black powder was confirmed by the owner, it was not found in the old bunker where it should be. In fact black powder was not found at all except within the recovered items.
- test performed by TNO-PML on display fireworks articles with similar pyrotechnic substances as were recovered indicate a HD 1.1 hazard rather than a HD 1.3 hazard.
- recovered items were similar to items responsible for an explosion of a fireworks factory in the UK.

Definite indications for the direct cause of the explosion were not found.

It is recommended to make an evaluation of the damage caused by the explosion in relation of the criteria of the quantity distances as recommended by the AC/258 storage group. This should be done especially for the fragment and debris criterion for HD 1.1 as large pieces of steel girders were thrown far beyond the 400 m circle.

It is recommended to require classification procedures for display fireworks. Not only for transport conditions but for fabrication, assembling and storage conditions also. The application of classification results for transport conditions to other circumstances as is usual presently must be strongly rejected.

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ABSTRACT

On February 14 1991 a heavy explosion completely destroyed the assembly plant for display fireworks "MS Vuurwerk" in Culemborg, The Netherlands.

An Investigation was carried out in order to determine the strength of the explosion on basis of damage caused to the buildings in the vicinity.
The damage was severe and extended a large area.
Therefore. an investigation was performed to determine the kind of articles involved and the Hazard Division they belong to.

The paper describes the accident, the damage analysis and the remaining doubts and questions.
Special attention will be paid to the relation between the (possible) differences between transport and storage classification.

EXPLOSIVE ACCIDENT SUMMARY: WORLD WAR II

-by-

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ABSTRACT

The DoD Explosives Safety Board is developing an electronic data base which lists and characterizes explosive accidents stored in historical files. While this data base is far from complete now, it may someday serve as a standard reference for the complex anatomy of explosive incidents. Accidents exact a tragic value: their causes give us clues to prevent recurrence, and their effects provide insight to those who design safety into operating facilities. While accident investigations fail to quantify phenomena to the degree that we obtain from explosives testing, they painfully substantiate hazards and underwrite safety programs.

In the course of searching historical files, a summary of World War II explosive accidents appeared which may be of interest to the field. While the explosions listed in this collection are not presented in depth, many are detailed in the classic abstracts written in the 1940's by the Office, Chief of Ordnance. They are the foundation upon which the Ordnance Safety Program was built.

Many of these disasters may not be familiar even to those who served.

BACKGROUND

The DDESB has accumulated a file of approximately 2,400 explosive accidents from around the world. The file was begun in the late 1940's by Dr. Ralph Ilsley and Mr. Bob Herman who drew upon the classic work of Ralph Assheton's "The History of Explosions," first published in 1930, which reported explosions characteristic of the dynamite and black powder days of the nineteenth century.[1] To Assheton's work, Ilsley and Herman added case histories of explosions from international sources and from accidents reported by the civilian and military authorities in the United States during the early 20th Century.

Dr. Ilsley compiled this collection into a work known as the "Explosion Log," so named because it "logs" distances from the seat of an explosion to points where various targets were located, describing the damage experienced by that target.

Aside from Ralph Assheton and Dr. Ilsley, C. S. Robinson of MIT compiled a similar damage log.[2] The blast effects of these three accident logs were compared in a paper written by this author in the minutes of the 2nd Australian Explosives Safety Seminar.[3]

The DDESB is in the process of listing its 2,400 accidents into a computer data base. When this task is completed, explosive events long obscured in history will emerge, bringing renewed opportunity for study, comparison and analysis. This paper presents a status report. This report will cover the World War II years, chosen as an easily identifiable period of history and because excellent records exist now, but may be on the verge of extinction.

EARLY ACCIDENT ABSTRACTS

The Safety and Security Branch of the Office, Chief of Ordnance, located in Chicago, in the early 1940's published 135 accident abstracts, detailing the causes, effects and corrective actions for explosive accidents occurring in the ammunition plant complex during the war years between 1941 and 1944. Obviously, these accidents are somewhat dated by the technology of the period.

These reports prompted the advance of explosives technology. They recommended discontinued use of super sensitive materials and processes; they suggested the protection of personnel from the direct exposure to blending, pressing and mixing operations; they outlined plans for improved engineering methods to prevent specific insults to explosives in process, and introduced material science studies to prevent incompatibility with them. They are worth the effort to study.

We also value these old reports because of the excellent techniques employed in investigation and analysis of accidental explosions. Findings and recommendations in these abstracts may be the foundation of the old Ordnance Safety Program, one of the first to bring the elements of engineering, accident analysis, development of procedures (SOP's), job training and the like into one cohesive management device.

This collection of accident abstracts continued beyond the war years through the Department of Army, Office, Chief of Ordnance, Washington D.C. which analyzed 252 explosions between 1945 and 1962. Some of these abstracts address explosive test programs and various conferences which examined specific problems such as the safe operation of melt units.

THE PRODUCTION BASE

Table 1 is a tabular list of production base accidents that were reported by abstracts and other Ordnance Corps files during World War II. While damage costs are also shown, remember that a home in World War II might cost 8 to 10 thousand dollars, and a new car about $2,200. The total accident cost of $4,457,464 for the 667 explosions and fires occurring in the production base during World War II might be increased by a factor of one hundred to reflect realistic costs today. The death toll was 314 people, about that number who might perish in traffic during a holiday week-end. This is a remarkable record when kept in perspective. (Estimates of fatalities as a result of hostilities in World War II amount to about 300,000 per month.)

Navy Depots and Production Plants. Much of the Navy's production base is also included in Table 1. Obviously, those Navy bases which did not report through the Ordnance Department were not included. The DDESB files contain seven reports with a total of 58 fatalities during the war years. Twenty six fatalities occurred at the old NAD Hastings, 11 at NAD McAlester and 8 at NAD Yorktown.

Installations are ranked below in terms of the number of fatalities experienced due to explosions in World War II.

Location	Incidents	Fatalities
1 Elwood Ordnance Plant	4	53[a.]
2 Iowa Ordnance Plant	15	36[b.]
3 NAD Hastings	3	26[c.]
4 Triumph Explosives Co	41	23[d.]
5 King Powder Co (All plants)	17	12
6 Portage Ordnance Depot	1	11[e.]
7 NAD McAlester	1	11[f.]
8 Cornhusker Ordnance Plant	2	7
9 Louisiana Ordnance Plant	16	7
10 Remington Arms Private Plant	6	7
11 Radford Ordnance Plant	26	7

PLANT DISASTERS

a. An explosion involving a building and 3 railcars of anti-tank mines with an explosives weight of 62,600 pounds of TNT, killed 49 and injured 67 on 5 June 1942. In terms of lives lost this was the most deadly explosion at the ammunition plants during World War II. Only 4 more were killed at the Elwood site during the rest of the World War II, despite the millions of tons of ammunition loaded there.

b. Five days after the attack on Pearl Harbor, the first World War II melt tower detonated at Iowa, killing 13 and injuring 53. Three months later on 4 March 1942, a second melt tower detonated with 22 fatalities and 84 injuries. The second accident caused a high loss of life because it occurred during shift change. These events were used to critically examine the safety of melt towers throughout the complex, resulting in hundreds of engineering changes and vast improvements in the operation of these units.

c. On 15 September 1944 a detonation of 550 tons of Torpex-loaed mines detonated in a Cooling Building with ten loaded railcars alongside, killing 10, and injuring 61. Barricaded on both sides, the blast carved a crater measuring 525 in length, 140 feet wide and 30 feet deep. Structural damage was registered at 3,500 feet, window breakage at 15 miles. Chunks of concrete weighing 500 pounds were thrown a mile. One was found at 7,300 feet.

A similar accident occurred in April of 1944 when Cooling Building 180, also barricaded on two sides, detonated, killing 8 and injuring 2. Two railcars alongside were involved for a total of 110,000 pounds of Torpex. Again, massive concrete fragments littered the area for a distance of 3,200 feet. Strangely, one man was killed by a missile at 1,300 feet. Severe structural damage to competent buildings occurred at 800 feet, weaker buildings such as warehouses were damaged at 1,700 feet. Due to a number of explosions of this nature, the U.S. Navy no longer uses Torpex.

d. In Elkton, Maryland the Triumph Explosives Company experienced a detonation in a granulator on 4 May 1943 which propagated to four buildings, killing 15 and injuring 64. No one in the plant was aware that explosives overloads had completely defeated Q-D separations. The area was not designed for the production rate required by the war.

e. This accident occurred in an earth covered magazine loaded with fragmentation bombs with a net explosives weight (NEW) of 40,759 pounds of TNT. There were 10 men in the crew and only one body found. A man working in another magazine crew was killed at a distance of 450 feet from the detonation.

f. The similarity between this accident and the one in

e. above is sinister. On 5 December 1944, while loading Torpex loaded bombs from a trailer into an igloo magazine, a detonation in the magazine propagated to the trailer, killing all 11 of the magazine crew.

These eight accidents are the most catastrophic events in the production base during World War II. <u>One percent of the accidents in the production base accounted for 42.9 percent of the total fatalities</u>. This factor underwrites the cardinal principle of explosives safety: expose only the fewest people to the lowest amount of explosives for the least amount of time.

The graphic at Figure 1 indicates this lesson was well understood during the war. While the number of incidents gradually increased from 1941 through 1945, the number of fatalities and critical injuries decreased markedly. Minor injuries also decreased. The 1942 they numbered 3.1 injuries per explosive accident. In 1943 the rate was down to 1 then went up slightly to 1.1 in 1944, finally dropping to less than 1 minor injury per incident in 1945. This overall statistical record is remarkable.

PLANT ACCIDENTS by TYPE of OPERATION

Table 2 lists each major type of operation in the ammunition production base by the number of explosions, deaths, injuries -- including the ratio of fatalities and injuries per event -- experienced for each one. The list is organized "worst first" based on the ratio of fatalities per event. As you might expect, melt units top the list. The list also tells us which accidents are more likely to happen regardless of fatalities. It shows why mixing, screening and pressing operations are accomplished remotely, and suggests why others, perhaps blending, should be. (Most blending operations are accomplished remotely today.)

The causes of selected plant accidents are listed at Table 3. These causes are taken from the DoD Case File 342. This file contains a listing by location of all plant accidents reported to the Ordnance Department, the dates, numbers killed and injured, and sometimes a one line cause statement.

ARMY ACCIDENTS, CONUS

Ten explosions are recorded at army bases during the war, with a total of 13 fatalities and 41 injuries.

ARMY AND U.S. MARINE CORPS EXPLOSIONS, OCONUS.

Twenty-six accidents around the world caused 108 fatalities and 130 injuries due to explosives accidents in deployed areas. Three explosions at Army Air Fields resulted in 16 fatalities, each, normally associated with handling 500 pound Bombs. Two accidents involving troops handling land mines, killed 16 and 14 respectively. These accidents occurred while retrieving mines

previously set by U.S. combat engineers. Bad weather and fatigue were factors in these events. These events occurred in deployed areas near combat zones.

SHIP EXPLOSIONS

The most disastrous events in the history of chemical explosives involve ships. The most significant explosive accident in this country during World War II occurred at NAD Port Chicago (Concord, California) when 3.75 million pounds of HE detonated in railcars, on the dock and aboard the USS E.A. Bryan, killing 325 and injuring 392. No one inside of 1,000 feet survived, and no one outside that distance perished. Damage was carefully documented by Bob Herman in DDESB Technical Paper 6.[4] (AD 223344) Many of the current DoD Q-D standards are based on this report.

However the death toll on the USS Mount Hood was worse. This AE detonated in Seeadler Harbor, Manus Island in the Admiralties, just north of New Guinea on 10 November 1944 while crews were off-loading and on-loading ammunition from several barges at once.[5] This detonation killed 378 servicemen, and injured 400. Twenty one smaller crafts within 500 feet of the blast, vanished Ten ships where severely damaged within one half mile, and 26 other ships experienced fragment damage up to 6,600 feet. People ashore were knocked down at 2.5 miles.[6]

The disaster in Bari, Italy involving the SS Charles Henderson of U.S. registry, was yet worse. This detonation caused by handing 500 pound bombs loaded with Composition B, killed 542 and injured 1,800. It is believed the bombs were hooked and dragged to the well, then lifted without mats. The crew may have hurried because the contract paid by number of items lifted. Buildings along the waterfront were destroyed for 2,000 feet. Ships were severely damaged to 2,100 feet.

One of the more obscure accidents of the period happened in Pearl Harbor when 6 LCT's and 3 LTV's loaded with infantry ammunition, berthed side to side, caught fire during refueling operations. Within minutes detonations were propagating between barges while men attempted to move them out into the bay -- 127 were killed and 380 wounded.

A total of 12 accidental shipboard explosions were recorded during the war years with the devastating result of 1,817 fatalities and 2,777 injuries.

The Texas City explosion occurred in 1947 involving 5 million pounds of ammonium nitrate produced at the U.S. Ammunition Plants for the lend lease program. The ammunition plants manufactured ammonium nitrate for bomb fill. However, this is not included as a wartime incident. (The SS Fort Stickine in Bombay killed 741, injuring 2,000 during the war, but this was not a U.S. accident.)

SURFACE TRANSPORTATION ACCIDENTS

During World War II, railroads and trucking firms moved almost 10 million tons of ammunition and explosives. There were a total of 16 significant explosions and fires on rail lines with 2 fatalities reported. There were also 16 significant explosions involving truckloads of explosives, but 11 were killed.

The most striking of these events occurred at Selma, North Carolina on 7 March 1942 when a passenger car ran a stcp sign and collided with a truck carrying 8,000 pounds of TNT and Tetryl. The truck drivers rescued the passengers from the burning car, but one of them died later. The fire department attempted, without success, to move the spectators away. A car with two passengers was actually driving past the burning wreck when it detonated, killing them. Fifty were injured in a dance hall 525 feet away. Two perished in a hotel fire 150 from the blast. Seventeen buildings were burned or structurally damaged, including a two story brick hotel. The final toll was 7 dead and 50 injured.

The record of transportation accidents involving ammunition and explosives is shown below. These numbers represent the total number of fires and explosions resulting from railroad and highway accidents in the period. The fatalities listed are those directly related to fire and explosions:

	Railroad		Truck	
	Events	Killed	Events	Killed
1942	1	0	2	8
1943	3	0	4	3
1944	7	1	5	0
1945	5	0	5	0
Total	16	1	16	11

SUMMARY

The following table of numbers will summarize the accidents considered by this report. There is no way to assure this record is complete, but its certainly the majority of significant incidents reported by U.S. authorities during the war years.

	Incidents	Killed	Injuries
Plants	667	314	9,000
Army (US)	10	13	41
Overseas	26	108	130
Ships	12	1,817	2,777
Transport	32	13	-
	747	2,265	4,033

HISTORICAL SOURCES

1. The Accident Log by Dr. Ralph Ilsley, 1796-1952: Lists damage logs for 384 cases. Ilsley's Log opens with Mr. Assheton's list of accidents (Ref 1), then adds those cases reported to DoD from various sources around the world, including many from within the Services. About 130 of these cases report World War II events.

2. The Department of Army Office of the Safety and Security Branch, Office of the Chief of Ordnance, Chicago, IL 1942-1944: These abstracts list 135 ammunition plant accidents including Government Facilities, Government-Owned-Contractor-Operated (GOCO) plants as well as private installations without dates or locations.

3. The Department of Army Office of the Chief of Ordnance, Wash DC, 1945-1962: These abstracts, listing 252 cases, echo those started in 1942. They are included only for reference since they cover the time after 1945.

4. The Army-Navy Explosives Safety Board, Wash DC 1944-1946: These one page abstracts report 38 World War II accidents from around the world.

5. Ordnance Field Safety Office, U.S. Army, Jeffersonville, IN, 1940's: These abstracts record about 55 cases, but are not always complete. Fortunately they duplicate other reports.

6. DoD File 1070. This is a comparison of truck versus rail transportation accidents involving ammunition and explosives from 1941 thru 1955. This information was gathered by an attorney for a lawsuit in the 1950's involving the safety records of railroads and truck companies.

7. DoD File 340. This file includes the history of World War II explosion and fires occurring in the production base

THE FUTURE OF ACCIDENT REPORTING

The accidents outlined above are prime examples of total system loss. They demonstrate the unraveling of management objectives, ultimate failures of communication, the weakening or loss of an entire span of human control. They combine horror with grief and tragedy. They destroy the workplace and cause loss of mission and pride of accomplishment. And, of course, they kill. Explosive accidents may, in fact, define the limits of human ability.

There is only one good thing, one truly positive aspect that may come from an explosive accident: the salient fact which may be

the key to preventing the next one, or to protect us from it. There is no other reason to exhume the events in this paper. We owe it to those who have gone before us, and to their families. It is the only debt we can pay. We may prevent future tragedies only when accidents are reported, analyzed and studied in a rational light.

Today, the system for reporting and analyzing accidents is hampered by threat of litigation. This threat inhibits both the gathering and reporting of evidence surrounding accident causes and effects. From the pure safety standpoint, establishing blame for an accident has little or no value in accident prevention.

There is a natural tendency to seek fault in those most closely associated with an accident. There may be a psychological need for this. But an accident is always a fault. Without human error there would be few, if any, accidents depending upon your definition.

(Webster: "2a: A sudden event or change occurring without intent or volition through carelessness, unawareness, ignorance, or a combination of causes and producing an unfortunate result "

This should be the premise, not the conclusion of accident investigations. We should discover unsafe acts before the explosion, including carelessness and failure to observe procedures -- these facts should be a matter of record along with the plans for corrective action. After the blast, the careless operators -- the uninstructed ones, may be gone, and the blame is moot. The primary reason for the the safety professional to study explosive accidents is the search for preventive measures, not blame.

The data base runs at the appendix may not list all the accidents reported in the body of this report, so the totals will not always match.

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TABLE 1

EXPLOSIVE ACCIDENTS IN U.S. FACILITIES DURING WORLD WAR II
(Including Fires Involving Energetic Materials)

Year	Incidents	Deaths	Critical	Injured	Cost
1941	8	15	10	42	$369,307
1942	95	148	58	295	$1,310,415
1943	223	88	72	219	$1,253,119
1944	268	53	15	321	$1,303,640
1945*	73	10	11	42	$220,983
Total	667	314	166	919	$4,457,464

U.S. Facilities Included in this Table

Both Private & Government-Owned Ammunition Plants

Arsenals, Depots, Test & Proving Grounds

TABLE 2

CATEGORIES OF WORLD WAR II PLANT ACCIDENTS

Type	Events	Deaths	Injuries	Fatals per Event	Injury per Event
Melt Units	5	46	122	9.2	24.4
Pack Out	15	81	182	5.4	12.1
Magazine Storage	4	17	3	4.3	0.8
Assembling	20	72	151	3.6	7.6
Blending	11	13	49	1.2	4.5
Rework	7	8	12	1.1	1.7
Maintenance	10	9	118	0.9	11.8
Burning Ground	21	17	22	0.8	1.0
Transfer	6	4	8	0.7	1.3
Transportation	11	7	10	0.6	0.9
Laboratory	8	5	4	0.6	0.5
Testing	15	9	25	0.6	1.7
Dry House	14	7	10	0.5	0.7
Loading	19	8	49	0.4	2.6
All Other	117	48	229	0.4	2.0
Nitration	24	9	28	0.4	1.2
Ready Storage	20	7	20	0.4	1.0
Screening	22	6	6	0.3	0.3
Drying	8	2	2	0.3	0.3
Mixing	34	7	14	0.2	0.4
Hammer Mill	6	1	3	0.2	0.5
Charging	12	2	17	0.2	1.4
Drilling	7	1	23	0.1	3.3
Pressing	44	6	57	0.1	1.3
Pelleting	8	1	2	0.1	0.3
Roll Mills	12	1	8	0.1	0.7
Grinding	12	0	2	0.0	0.2
Totals	492	394	1176	0.8	2.4

TABLE 3

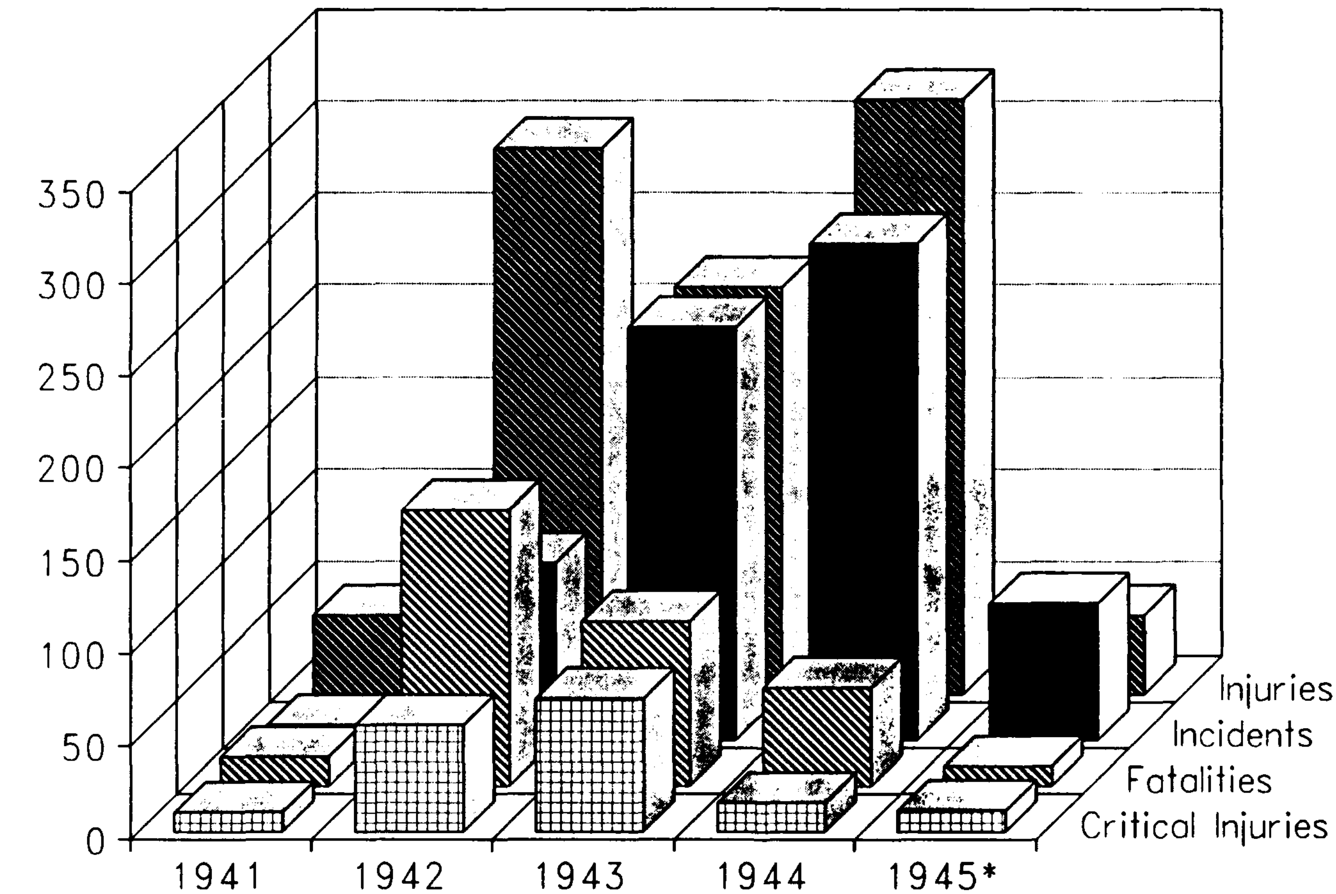
CAUSES OF SELECTED PLANT ACCIDENTS

Unknown	221
Procedural	107
Heat	42
Static/Spark	42
Impact/Friction	48
Dropped/Fell	12
Tramp Material	11
Mechanical	22
Lightning/Storms	17
Maintenance	11
Various Specific	11
Total Examined	544

Keys:

Unknown:	Either evidence inconclusive, or no investigation was conducted.
Procedural:	Human error, SOP violation, regulation violated.
Heat:	Fires, spontaneous ignition, flame production
Static/Spark:	Static discharge, spark from flames or any other source.
Friction: (Impact)	All causes linked to these insults.
Dropped/Fell:	Explosive bumped or dropped, or when something fell on explosive.
Tramp Material:	Foreign material in process, such as grit or metal.
Mechanical:	Leaks, metal breakage, valve failures, press failures (shots)
Lightning: (Storms)	Caused by lightning effects, winds or other storm related phenomena
Maintenance:	Working on explosives contaminated equipment or facilties.
Various:	Design errors, cigarettes, chemical reactions, deterioration of explosives.

ACCIDENTAL EXPLOSIONS IN US FACILITIES
Ammunition Production Base



World War II Explosions
Army Class 1 Installations

Installation	Location	Date	Type	Items	Operation	Dead	Injured
Air Field	Chelveston	UK 09/03/43	Combat	Bombs, M43	Aircraft, B-17F Bomber	0	0
Ft Benning	Ft. Benning, GA	US 07/29/44	Storage	Ammunition, Smoke	Magazine, Igloo	0	0
Camp Blanding	Camp Blanding, FL	US 09/06/44	Storage	Grenade, M15, M1	Open Stacks	0	0
Firing Range	Algiers	DZ 10/22/43	Range	Projectile, M107	Howitzer, 155mm	8	6
Camp Beal	Camp Beal, CA	US 08/19/43	Training	Bomb, Demolition	Fighter A/C P-30	2	0
Henderson Field	Guadalcanal	US 11/27/44	Storage	Ammunition	Open Storage	1	0
Tactical Mine Field	Wittring	FR 01/19/45	Loading Truck	Mines, AT	Truck	16	10
Ft Knox	Ft Knox, KY	US 07/19/42	Storage	Mortar, 81mm, Gun, 75mm	Magazine, Igloo No 14	0	0
Army Air Field	Medfield	UK 07/15/44	Loading Truck	Bombs, GP 1000 lbs	Trucks	0	0
Mitchell Field	Long Island, NY	US 01/01/42	Aircrash	Bomb, GP 500 lb	Aircraft, B-25 Bomber	5	0
Army Air Base	Navarin	DZ 06/26/43	Loading Truck	Bombs 500 lb	Open Storage Pads	16	0
Field Operation	APO 958	05/17/45	Maintenance	Fuze, M600, Chemical		0	0
Camp Polk	Camp Polk, LA	US 06/16/44	Storage	Projectile, 155mm	Magazine, Igloo	0	0
Camp Pickett	Camp Pickett, VA	US 11/04/43	Handling UXO	Rocket, HE, M6A1	Training Range	5	38
Army Air Force Station	Ridgewell	UK 07/29/43	Combat	Bombs 500 GP	Aircraft, B-17 Bomber	23	0
East Field	Saipan	01/19/45	Aircrash	Bombs, 500 lb SAP	Open Storage	15	38
Air Field	Deenethorpe	UK 06/12/44	Loading A/C	Bombs, Frag	Aircraft	0	0
Mine Field	Camp Breckinridge, KY	US 08/09/44	Training	Mine, AT	Mine Field	0	1
Mine Field	Fornace	IT 01/08/45	Combat	Mines, AT	Mine Field	14	18
Army Air Field	Chelveston	UK 08/27/43	Combat	Bombs, 500 lb	Aircraft, B-17 Bomber	0	0
*** Total ***						105	111

World War II Explosions
Ships

Installation	Location	Date	Type	Items	Operation	Dead	Injured
SS Charles Henderson (US)	Bari	IT 04/09/45	Loading Ship	Bombs, 500 lb AN-M64	Dockside Cranes	542	1800
SS John Burke (US)	Pacific Theatre	12/28/44	Combat	Bombs, HE & WP	Ship & LST's	300	23
USS Colorado	Iwo Jima	JA 04/20/45	Loading Ship	16" Charge, Mk 5 Tank	Ships Magazine	1	3
SS John M Brook (US)	Bari	IT 03/02/45	Loading Ship	Bombs	Loading tray	0	4
USS South Dakota	Pacific Theatre	05/06/45	Loading Ship	16" Chg, Mk 5 Tank	Ships Magazine	11	22
SS El Estero	Caven Point, NJ	US 04/24/43	Trans	Ammunition	Ship	0	0
USS Serpens	Guadalcanal	US 01/29/45	Loading Ship	Bombs	Ship	194	15
USS Hancock	China Sea	01/21/45	Combat	Bomb, 500 lb, GP, AN-M64	Flight Deck	50	81
LTV Alongside USS Latimer	South Pacific	12/21/44	Tactical Ship	Grenades, Rifle, Thermate	LTV	0	0
NAD Port Chicago	Concord, CA	US 07/17/44	Loading Ship	Ammunition	USS E A Bryan	325	392
Seeadler Harbor	Manus Island, Admiralties	AS 11/10/44	Loading Ship	Ammunition	USS Mt Hood	378	400
Pearl Harbor	Pearl Harbor, HI	US 05/21/44	Loading Barge	Ammunition	6 LST's & 3 LCT's	127	380
*** Total ***						1928	3120

World War II Explosions
Navy Installations Ashore

Installation	Location	Date	Type	Items	Operation	Dead	Injured
NAD Hastings	Hastings, NE	US 04/06/44	LAP	Bombs and Mines	Cooling Building	8	2
NAD Hastings	Hastings, NE	US 09/15/44	Loading Railcar	Bombs, Depth	Transfer Dock	10	56
NAD Hastings	Hastings, NE	US 07/19/45	Disposal	Bombs	Demolition Area	8	0
NAD Hawthorne	Hawthorne, NV	US 03/03/45	Storage Ops	Box of Gas Tank Igniters	Magazine, Igloo	0	0
NAD McAlester	McAlester, OK	US 12/05/44	Storage Ops	Torpedo Warheads	Magazine, Igloo	11	0
NAS Norfolk	Norfolk, VA	US 09/17/43	Trans	Depth Bombs, AN-Mk47	Airfield Taxiway	27	399
NAD Oahu	Oahu, HA	US 06/11/44	Storage Ops	Torpedo Whds (Air & Sea)	Magazine, Tunnel Type	10	3
NPP Indian Head	Indian Head, MD	US 04/19/45	Mfg	Single Base Smokeless	Solvent Recovery	3	0
NAD Yorktown	Yorktown, VA	US 11/16/43	Loading Truck	Mines, M-16-1	Warehouse	8	6
*** Total ***						85	466

World War II Explosions
High Injury & Death Toll

Installation	Location	Date	Type	Items	Operation	Dead	Injured
Louisiana Ord Plant	Shreveport, LA	US 11/27/42	LAP	Bomb M58 (Fragmentation)	Unapproved Tool	5	25
Camp Pickett	Camp Pickett, VA	US 11/04/43	Handling UXO	Rocket, HE, M6A1	Training Range	5	38
Highway	Selma, NC	US 03/07/42	Trans	Bursters M5	Tractor Trailer	7	50
NAD Hastings	Hastings, NE	US 04/06/44	LAP	Bombs and Mines	Cooling Building	8	2
NAD Hastings	Hastings, NE	US 07/19/45	Disposal	Bombs	Demolition Area	8	0
NAD Yorktown	Yorktown, VA	US 11/16/43	Loading Truck	Mines, M-16-1	Warehouse	8	6
Cornhusker Ord Plant	Grand Island, NE	US 05/26/45	LAP	TNT Molten	Melt Pour	9	6
Ammunition Dump, Okinawa	Okinawa Island	JA 07/10/45	Loading Truck	Mines, Japanese	Open Storage	9	0
NAD Hastings	Hastings, NE	US 09/15/44	Loading Railcar	Bombs, Depth	Transfer Dock	10	56
NAD Oahu	Oahu, HA	US 06/11/44	Storage Ops	Torpedo Whds (Air & Sea)	Magazine, Tunnel Type	10	3
NAD McAlester	McAlester, OK	US 12/05/44	Storage Ops	Torpedo Warheads	Magazine, Igloo	11	0
Portage Ord Works	Ravenna, OH	US 03/24/43	Storage Ops	Bombs, Frag M-41	Magazine, Igloo	11	3
Ordnance Plant	East Rochester, NY	US 09/06/42	Mfg	Flare Comp & Black Powder	Flare Assembly Line	11	13
Edgewood Arsenal	Aberdeen, MD	US 05/25/45	LAP	Igniters, M13	Air Tool	12	50
Terminal Island, Dock 223	San Pedro, CA	US 10/21/44	Industrial	Toluene	Two LSM's	12	16
Tinian	Mariana Islands	US 03/07/45	Storage Ops	Mines	Trucks	12	7
Rochester Fireworks Plant	Rochester, NY	US 11/06/42	Mfg	Signals, MKII, Red Star	Operating Building	12	11
Iowa Ord Plant	Burlington, IA	US 12/12/41	LAP	Mortar, 81mm	Melt Pour	13	53
Triumph Explosives Co	Elkton, MD	US 05/04/43	Mfg	Tracer Mix	Stokes Granulator	15	64
Eglin AFB	Pensacola, FL	US 07/12/43	Training	Demolition Blocks	Tree Stumps	17	50
Lighter at Sea	Boston Harbor, MA	US 05/13/44	Disposal	Ammunition	Lighter, 132 Foot	17	0
Iowa Ord Plant	Burlington, IA	US 03/04/42	LAP	Bombs, 500lbs GP	Melt Pour	22	84
NAS Norfolk	Norfolk, VA	US 09/17/43	Trans	Depth Bombs, AN-Mk47	Airfield Taxiway	27	399
Elwood Ord Plant	Joliet, IL	US 06/05/42	LAP	Mines, AT	Railcars	49	67
Pearl Harbor	Pearl Harbor, HI	US 05/21/44	Loading Barge	Ammunition	6 LST's & 3 LCT's	127	380

World War II Explosions
High Injury & Death Toll

Installation	Location	Date	Type	Items	Operation	Dead	Injured
USS Serpens	Guadalcanal	US 01/29/45	Loading Ship	Bombs	Ship	194	15
NAD Port Chicago	Concord, CA	US 07/17/44	Loading Ship	Ammunition	USS E A Bryan	325	392
*** Total ***						966	1790

THE U.S. ARMY SAFELOAD EXPLOSIVES SAFETY PROGRAM

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Robert A. Rossi

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For Ammunition Logistics
Picatinny Arsenal, NJ 07806-5000

ABSTRACT

The Safeload Program is designed to provide soldier-ready solutions that minimize existing explosive hazards and risks. The Safeload Program replaces a program called Quickload, which was started in 1984 to provide interim solutions to unsafe storage of basic loads of ammunition in ammunition holding areas in South Korea. While Quickload primarily focused on Korea, and secondarily on Europe, the Safeload Program addresses explosives safety problems in all theaters. Safeload solutions can be divided into two distinct categories: propagation control solutions and improvements to explosives safety technology. The program is an important part of the ammunition logistics objective: getting ammunition to the soldier. Explosives safety regulations tend to become a constraint to an organization's capability. By finding ways to remove these hurdles, Safeload increases an organization's flexibility, productivity, efficiency, effectiveness and safety.

INTRODUCTION

Operations Desert Shield and Desert Storm were the ultimate test of the Army's ability to quickly move huge quantities of ammunition from depots in the United States and storage locations overseas to combat forces deployed in a theater of operations. An extremely important element of ammunition logistics, particularly during a conflict, is the need for safety in both moving and storing ammunition. U.S. Army ammunition is well-known throughout the world as safe and thoroughly tested. However, if explosives safety standards are not considered when ammunition is stored in the field, the potential for a mishap increases, often with catastrophic results.

* This paper is scheduled for publication in the November-December issue of Army Logistician Magazine.

An accident at the close of Operation Desert Storm illustrates the importance of safety. At Camp Doha, Kuwait, a fire on a field artillery ammunition support vehicle detonated ammunition on the ground and in other vehicles. In the resulting explosion, 58 soldiers were injured, 84 vehicles destroyed, and 77 vehicles damaged. In all, more than $40 million worth of supplies, property, and equipment was lost. Several days later, two soldiers were killed and one injured when an explosion occurred during cleanup at the accident site.

After-action interviews revealed that the ammunition storage practices that led to this accident were not unusual. The potential danger was exacerbated by insufficient storage space for the large amounts of ammunition. Even with Saudi Arabia's large land mass in which to operate, security considerations and operational necessity often reduced the size of munition storage areas. The result was that explosives safety suffered. In sum, this was a classic case of how and why a real time explosives safety strategy is the commander's best friend in ensuring the availability and survivability of a precious asset.

AMMUNITION SAFETY PROGRAMS

Improvements to the $20-billion ammunition logistics system are the responsibility of the Project Manager for Ammunition Logistics (PM-AMMOLOG). PM-AMMOLOG has two programs for improving the overall safety of the ammunition logistics system: the Safeload Explosives Safety Program and the Explosives Safety Improvement Technology Program. The Safeload Program, funded by operation and maintenance, Army, appropriations, is designed to provide soldier-ready solutions that minimize existing explosives hazards and risks. It was created to respond directly to needs communicated from the field. A listing of Safeload Program projects are contained in figure 1. The Explosives Safety Improvement Technology Program, on the other hand, develops technology for safer munitions packaging and improved explosives safety for subsequent transition into the Safeload Program. It is funded by research, development, test, and evaluation appropriations.

The Safeload Program replaces a program called Quickload, which was started in 1984 to provide interim solutions to the unsafe storage of basic loads of ammunition in ammunition-holding areas in South Korea. While the original Quickload Program primarily focused on Korea, and secondarily on Europe, the Safeload Program addresses explosives safety problems in all theaters.

By reducing hazards and associated risks for our soldiers, the Safeload Program improves the survivability, operability, and sustainability of the ammunition logistics system. Survivability is strengthened because munitions that are safely stored can survive accidents and enemy attack. Operability is enhanced because, by using denser storage configurations and reducing safety-imposed constraints, limited storage space is freed for other purposes. Sustainability is upgraded because ammunition is safer to transport and can be stored uploaded and ready for movement at oversea depots. The payoff from Safeload advances is reduced safety violations, reduced hazard risks, and a safer flow of ammunition through the ammunition logistics system.

The Safeload Program complements the Army's Insensitive Munitions (IM) Program. While Safeload focuses on munitions in the current inventory, the IM Program develops less-sensitive high explosives and propellants, mitigation devices, and improved packaging. These improvements will result in munitions that will react less violently to unplanned stimuli. As new munitions incorporating these IM advances enter the inventory, they will enhance the explosives safety storage benefits provided by Safeload. The contributions of both the Safeload and IM Programs will result in the highest level of safety and survivability.

HOW SAFELOAD WORKS

New ideas for programs to address soldiers' explosives safety concerns are always solicited from the field. These concerns, along with potential solutions, are forwarded to the Army's major commands to determine the extent of user interest and applicability. Project funding is then requested for those projects that are needed and have support. All solutions to explosives safety problems are developed by PM-AMMOLOG in close coordination with the Army Technical Center for Explosives Safety and the Department of Defense Explosives Safety Board; those organizations must approve all solutions before they are implemented. Strong support is provided by the Army Training and Doctrine Command's Munitions System Manager. PM-AMMOLOG manages the projects and selects activities within the explosives safety community to execute individual projects, based on cost, scheduling, and performance factors.

Safeload solutions can be divided into two distinct categories: propagation control solutions and improvements to explosives safety technology. Propagation control solutions prevent an unplanned detonation from spreading to other munitions, which will greatly reduce the size of an accident and prevent a potential catastrophe. Typical propagation control

solutions include ammunition racks that store munitions or barricades that are placed between stacks of munitions.

Improvements to explosives safety technology which are now being planned include a computerized explosives site-planning program and a project to improve personnel protection from hazard division 1.3 explosive remote operations (which are mass-fire-producing items such as propellants and infrared flare mix). Other efforts, suggested by the U.S. Army, Japan's 83d Ordnance Battalion, include methods of using natural terrain (such as hills and cliffs) to reduce hazard zones; determining the TNT equivalency of propellants; and determining if the blast waves from improperly stored ammunition will coalesce.

A number of other projects identified by the explosives safety community are being considered for future efforts. These include portable safety boxes for arms-room storage of 75-millimeter salute cartridges; barricades to improve safety at ports during deployment; and energy-absorbing barricades to dissipate blast forces during accidents. The feasibility of these concepts is currently being evaluated.

CURRENT SAFELOAD PROJECTS

A number of successful solutions have already been completed and distributed to the field under the Safeload Program. Technical data packages containing detailed information are available by writing to--Director, U.S. Army Technical Center for Explosives Safety, ATTN: SMCAC-ESL, Savanna, IL 61074-9639. The applicability of these solutions to specific wartime or peacetime scenarios must be determined by the using organization. Many of these solutions were developed by the Army Ballistic Research Laboratory at Aberdeen Proving Ground, Maryland. They include ammunition storage racks for downloaded tank ammunition, a sand grid wall, a method for storing mixed munitions in a conex container; a TOW missile rack; and a 4.2-inch mortar rack.

The tank ammunition storage racks, figure 2, permit the safe storage of downloaded tank ammunition during periods of vehicle maintenance or unit training. Previously, the ammunition was simply removed from the tank and temporarily piled on the ground. The racks reduce the hazard radius for 105-millimeter ammunition from 1,200 feet to 50 feet, and the radius for 120-millimeter ammunition from 800 to 75 feet. These reductions in hazard radius are important when storage space is at a premium.

The sand grid wall, figure 3, allows truckloads of nearly all types of 155-millimeter artillery ammunition to be safely

stored with only a 15-foot separation between trucks. This is a substantial reduction from the standards in current safety regulations, which require a separation of 150 feet between trucks if unbarricaded and 82 feet if standard above-ground barriers are used (see figure 4). By placing the sand grid wall between uploaded trucks, up to 160 155-millimeter projectiles and an equivalent number of propellant charges can be stored on each truck. Sand grid walls are inexpensive, can be built by unskilled labor, and can be collapsed so they take up little storage space when not in use.

The Ballistic Research Laboratory has also developed a technical data package that describes a method for storing up to 500 pounds of hazard division 1.1 (mass-detonating items) bulk high-explosives or demolition material in a fixed conex container. With this method, the hazard radius for these materials is reduced from 1,250 feet to only 360 feet. Certain small-caliber ammunition, smoke grenades, ground illumination signals, and a file destroyer may also be stored in the container. This storage method also allows the space between conex containers in storage to be reduced from 96 feet to only 8 feet.

The TOW missile rack, figure 5, is used in a fixed conex container to reduce the size of an explosion and prevent mass detonations. The TOW rack reduces the hazard radius from 1,250 feet to only 350 feet, except at the door, where 740 feet is required for a 60 degree arc. Use of the rack reduces the land required to store 1 conex container full of TOW missiles from 113 acres to 14 acres.

The 4.2-inch mortar rack, figure 6, provides safe storage for 48 high-explosive mortar projectiles in a fixed conex container. Use of the rack reduces the hazard radius from 1,250 feet to only 100 feet, except at the door, where 310 feet is required for a 30 degree arc. The result is a reduction in land required from 113 acres to only 1 acre (see figure 7). The rack consists of simple wooden modules made of common lumber that are stacked inside a conex container to prevent round-to-round propagation. Plastic bottles filled with fire suppressive liquid are placed inside the modules. During an accident, the bottles will rupture, coating all wood with a fire preventative that inhibits cook-offs or secondary fires.

COMING SOLUTIONS

During 1993, additional solutions will become available to reduce hazards throughout the logistics system.

The Huntsville (Alabama) Division of the Army Corps of Engineers will produce three designs for small earth-covered magazines. These miniature magazines, or minimags, will provide secure storage for small quantities on munitions or explosives. They could be used to store explosive ordnance disposal operational loads and K-9 explosive scent kits; separate small quantities of incompatible items; or temporarily store amnesty items or munitions awaiting demilitarization. They could also be used by the research and development community. The magazines will be relatively inexpensive to build and will significantly reduce hazard-zone requirements. The magazines will also feature separated compartments to allow storage of ammunition from different compatibility groups.

A wartime storage risk analysis being performed at the Army Corps of Engineers' Waterways Experiment Station in Vicksburg, Mississippi, will provide numerical risk factors to help commanders make informed decisions when they must store ammunition closer together and closer to inhabited buildings than safety regulations permit. The need for these risk factors was suggested by soldiers participating in Operations Desert Shield and Desert Storm.

The Waterways Experiment Station is also developing a method of storing trucks or trailers uploaded with 155-millimeter artillery ammunition in excavated, covered trenches (see figure 8). The ammunition trucks will be parked rear-to-rear in the trenches, with a sand-wall barrier between them. This will allow trucks to be stored only 10 feet apart, instead of the normal, unbarricaded requirement of 150 feet. Trench storage will provide inexpensive and rapid construction, reduce hazard radiuses, and improve survivability from enemy fire. It will be ideal for desert environments since it provides camouflage and protects against sand and dust.

Troops routinely build sandbag walls between basic-load ammunition stored in the open, in vehicles, on trailers, or in conex containers. However, despite their widespread use, sandbag walls have many problems. Filling sandbags is slow work and requires much labor. Once sandbag walls are built, exposure to sunlight rapidly decomposes the sandbags and the walls quickly loose stability. In response to these problems, the Waterways Experiment Station is developing procedures for building a new type of sand or earth wall, called geosynthetic reinforced walls (see figure 9). Compared to sandbag walls, geosynthetic walls can be built at 1/3 the cost and in 1/8 the time, using materials that require only 1/8 the storage room, and will last 10 to 40 times longer. A step-by-step videotape and technical data

package will soon be available to demonstrate geosynthetic reinforced-wall construction techniques.

During Operations Desert Shield and Desert Storm, ammunition was stored in the open at ammunition supply points in Saudia Arabia. Attempts to construct sand barricades between ammunition stacks to prevent explosive propagation were frustrated by strong desert winds, which simply blew the barricades away (see figure 10a). In response, the Waterways Experiment Station is developing lightweight, portable, easily installed devices that will prevent the wind erosion of sand-term barricades used between basic-load ammunition in desert environments (see figure 10b). A step-by-step videotape and technical data package will be available to demonstrate the different erosion control techniques.

The PM-AMMOLOG's Safeload Program is an important part of the overall ammunition logistics objective: getting ammunition to the soldier. Explosives safety regulations tend to become a constraint to an organization's operational capability. By finding ways to remove these hurdles, Safeload increases an organization's flexibility, productivity, efficiency, and effectiveness. In short, explosives safety consciousness can be a significant force multiplier.

The Safeload program is designed to meet user needs and seek answers to soldier's explosives safety concerns. New ideas for future Safeload projects are encouraged and should be sent to the Office of the Project Manager for Ammunition Logistics, ATTN: AMCPM-AL, Building 455, Picatinny Arsenal, NJ 07806-5000. Together, we can make explosives safety a low-risk enterprise.

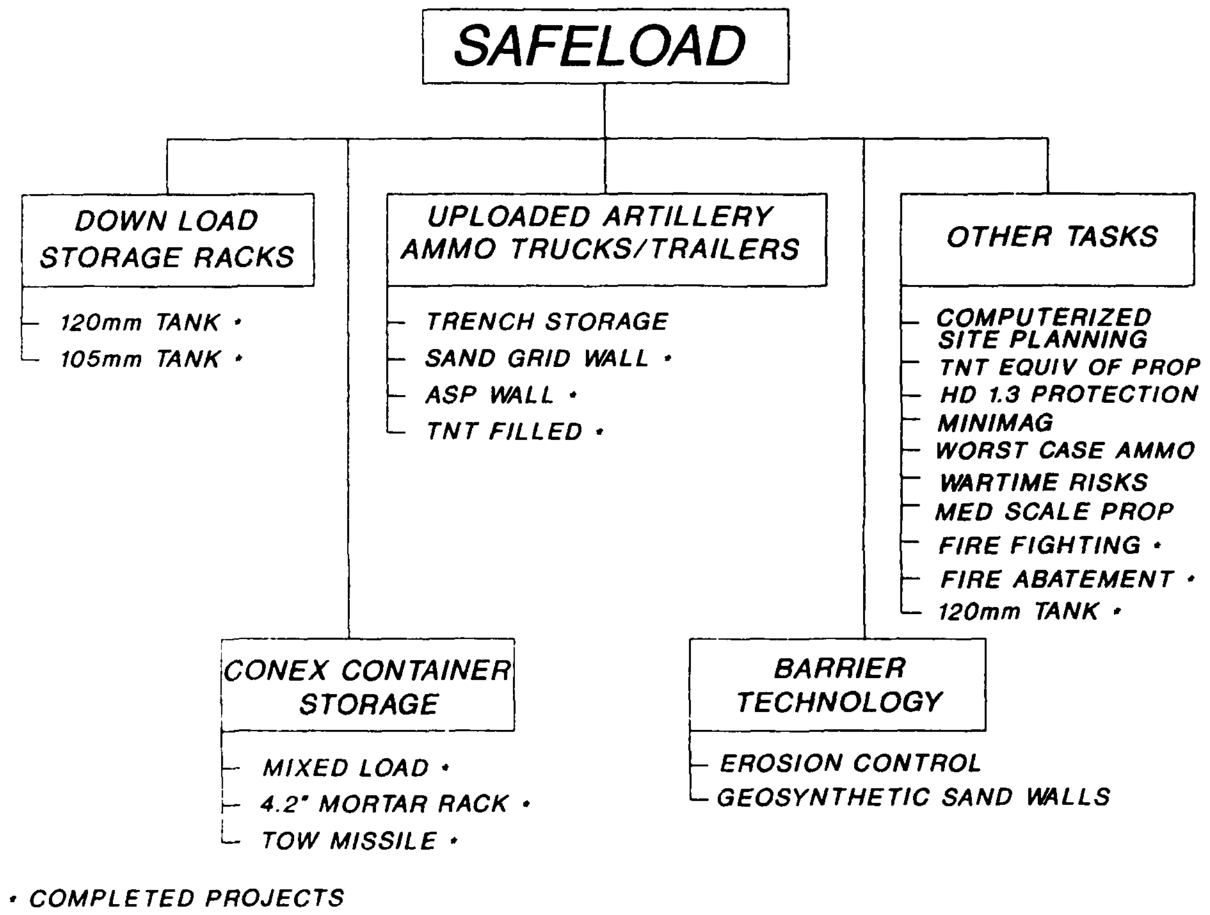


Figure 1. Projects in the Safeload Explosives Safety Program

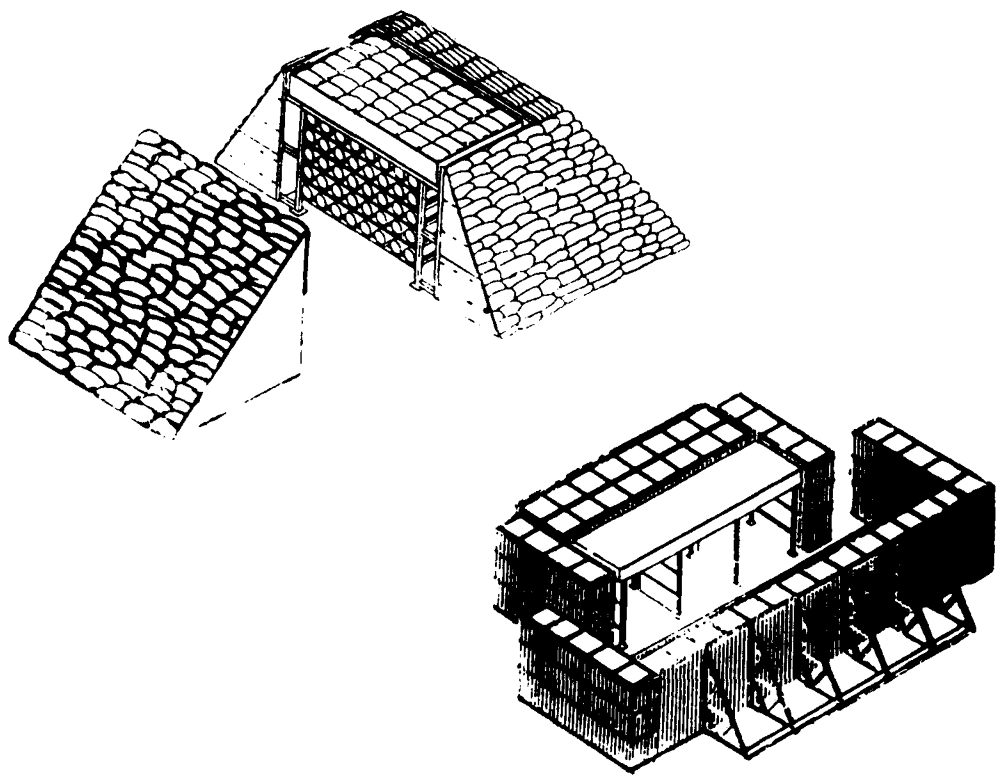


Figure 2. 105mm and 120mm Tank Ammunition Racks Provide Safe Storage During Maintenance or Unit Training

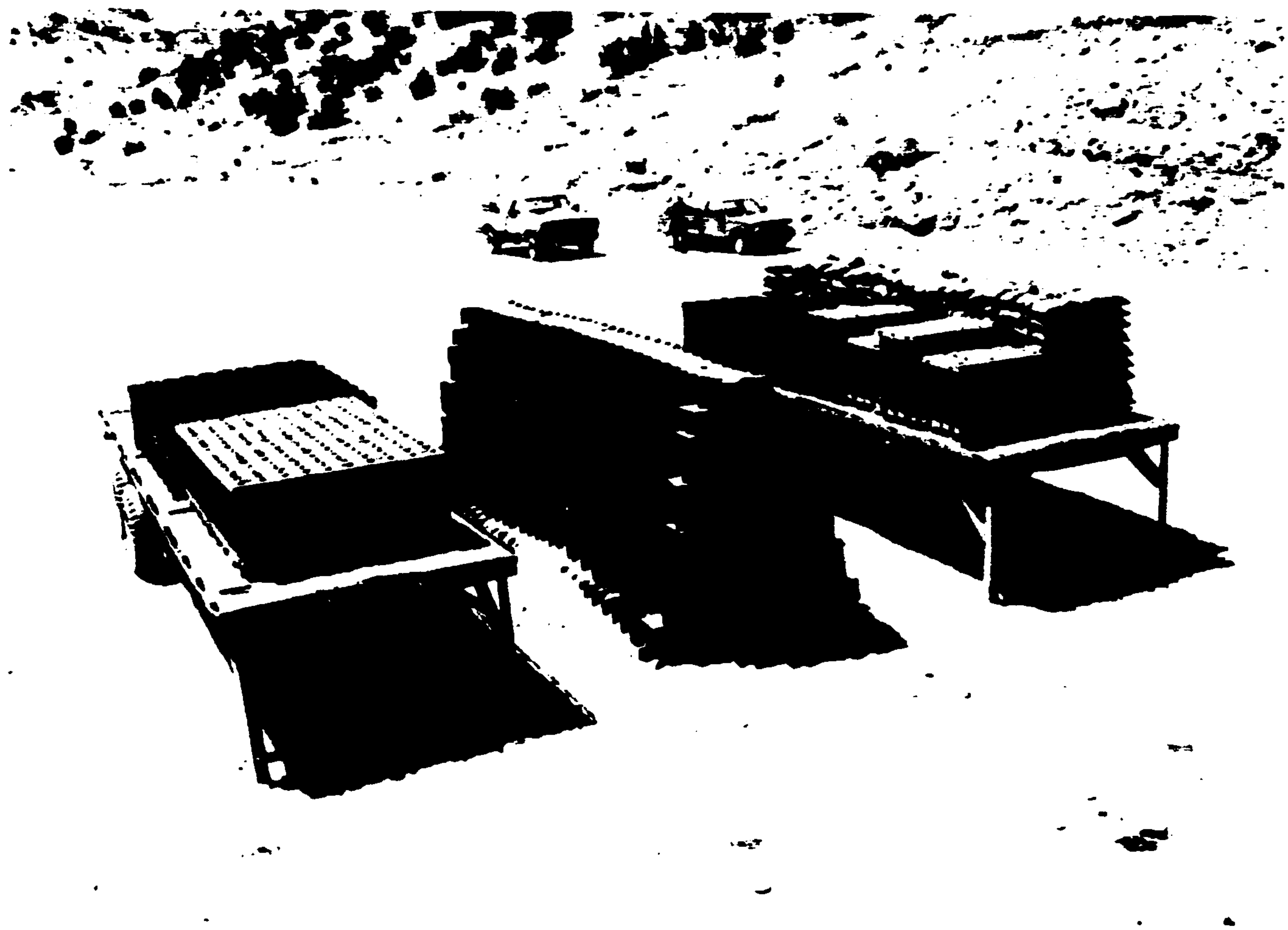


Figure 3. The Sand Grid Wall Prevents Explosive Propagation Allowing Loaded Ammunition Trucks To Be Closely Parked

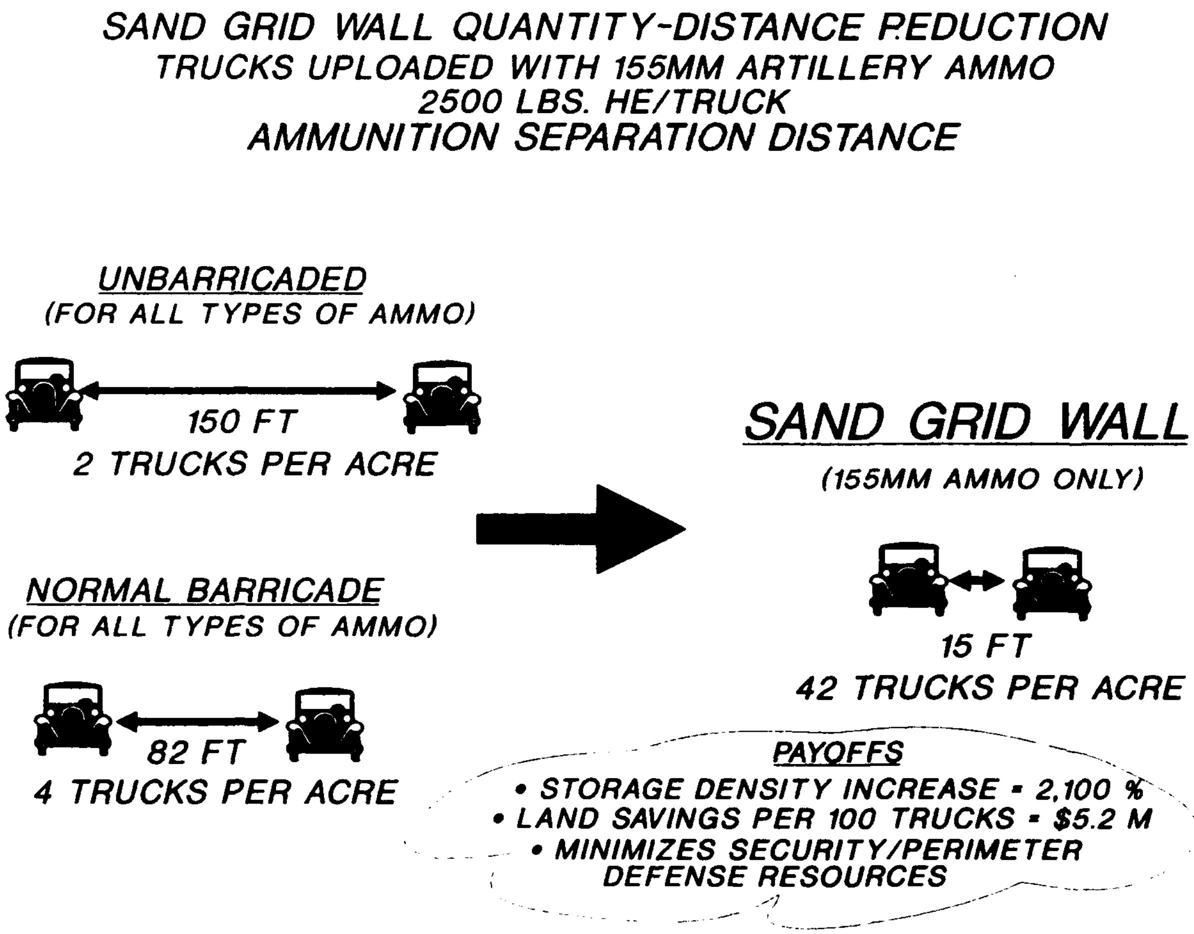


Figure 4. Operational Benefits of the Sand Grid Wall Barricade

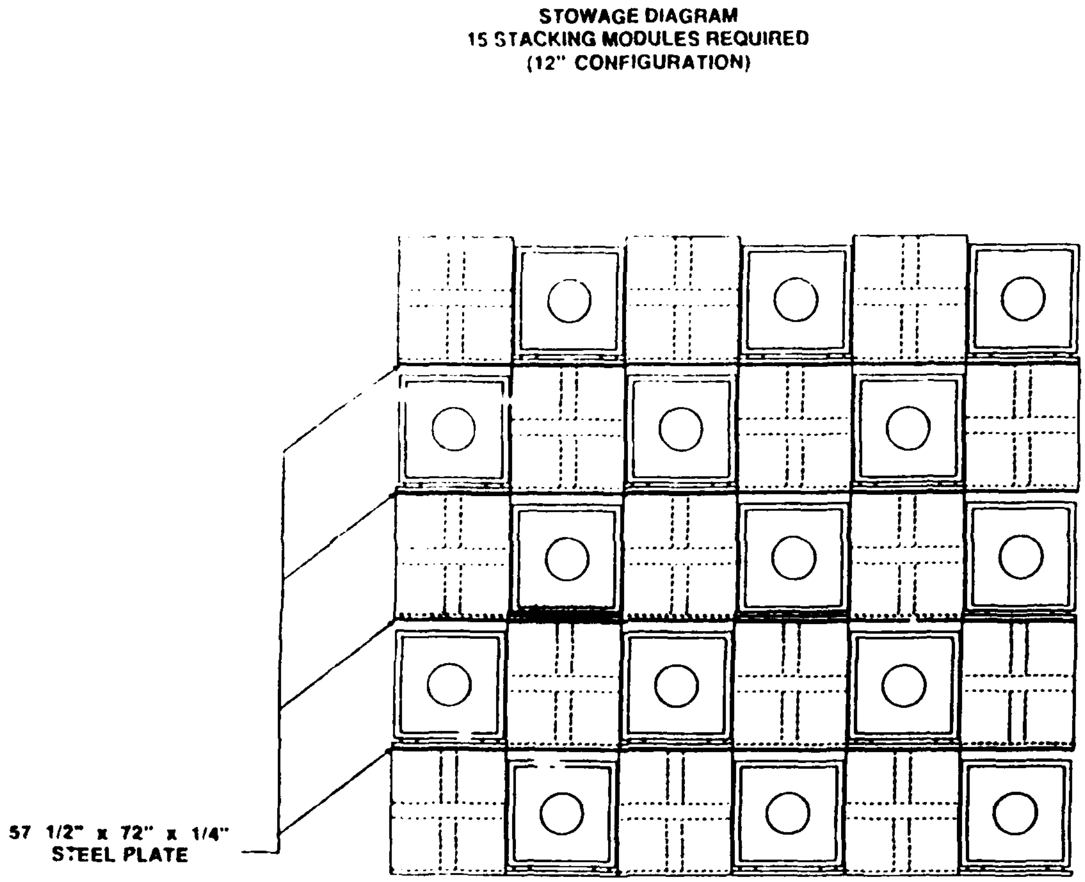


Figure 5. The TOW Missile Rack Provides Safer Storage in Conex Containers

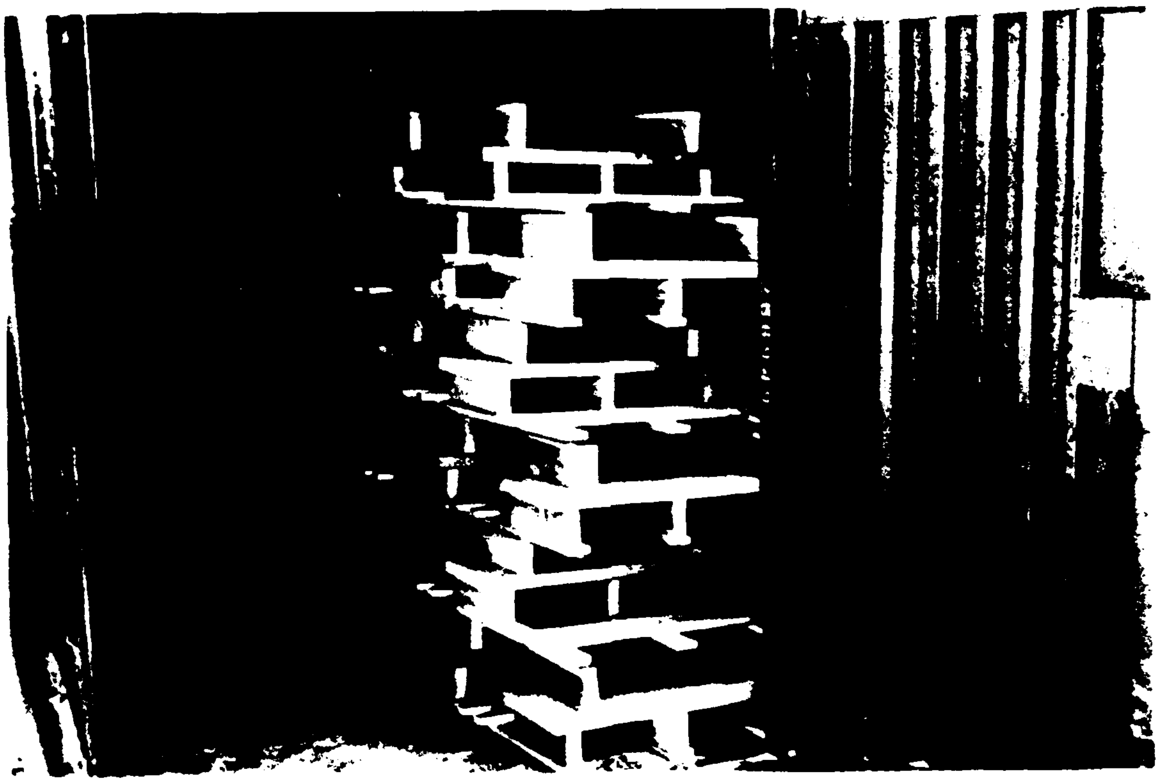


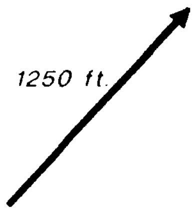
Figure 6. The 4.2 Inch Mortar Rack Provides Safer Storage in a Conex Container

QUANTITY DISTANCE REDUCTION

STORAGE OF 48 HE FILLED 4.2" MORTARS

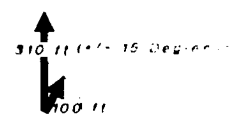
INHABITED BUILDING DISTANCE

CONEX WITHOUT RACK



REQUIRES 113 ACRES ENCUMBERED LAND

CONEX WITH RACK



REQUIRES 1 ACRE ENCUMBERED LAND

PAYOFFS

- STORAGE DENSITY INCREASE = 11,200 %
- LAND SAVINGS PER CONEX = $11.2 M

Figure 7. Hazard Zone Reduction Provided By The 4.2" Mortar Rack

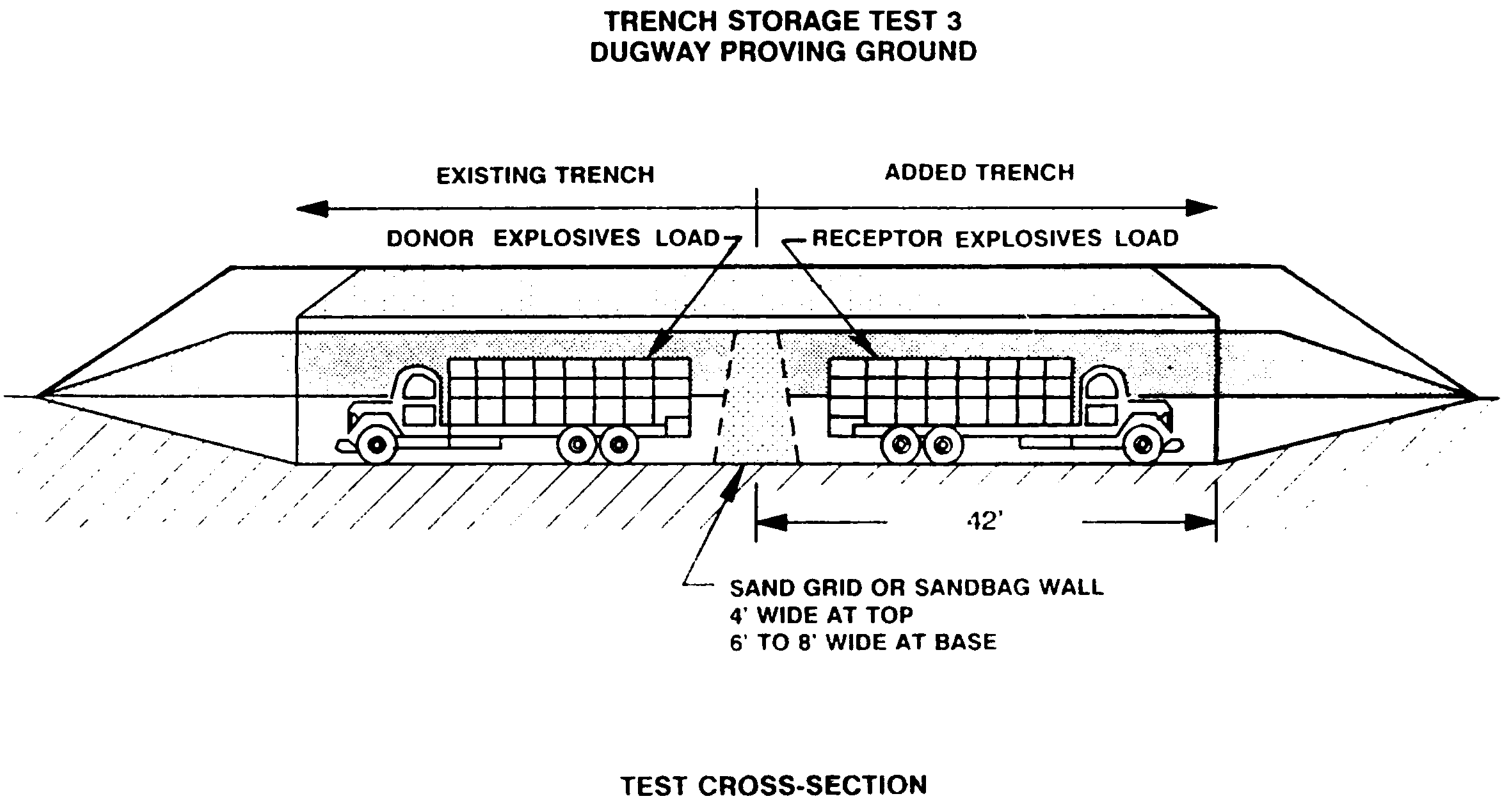


Figure 8. Trench Storage Provides Improved Safety And Survivability

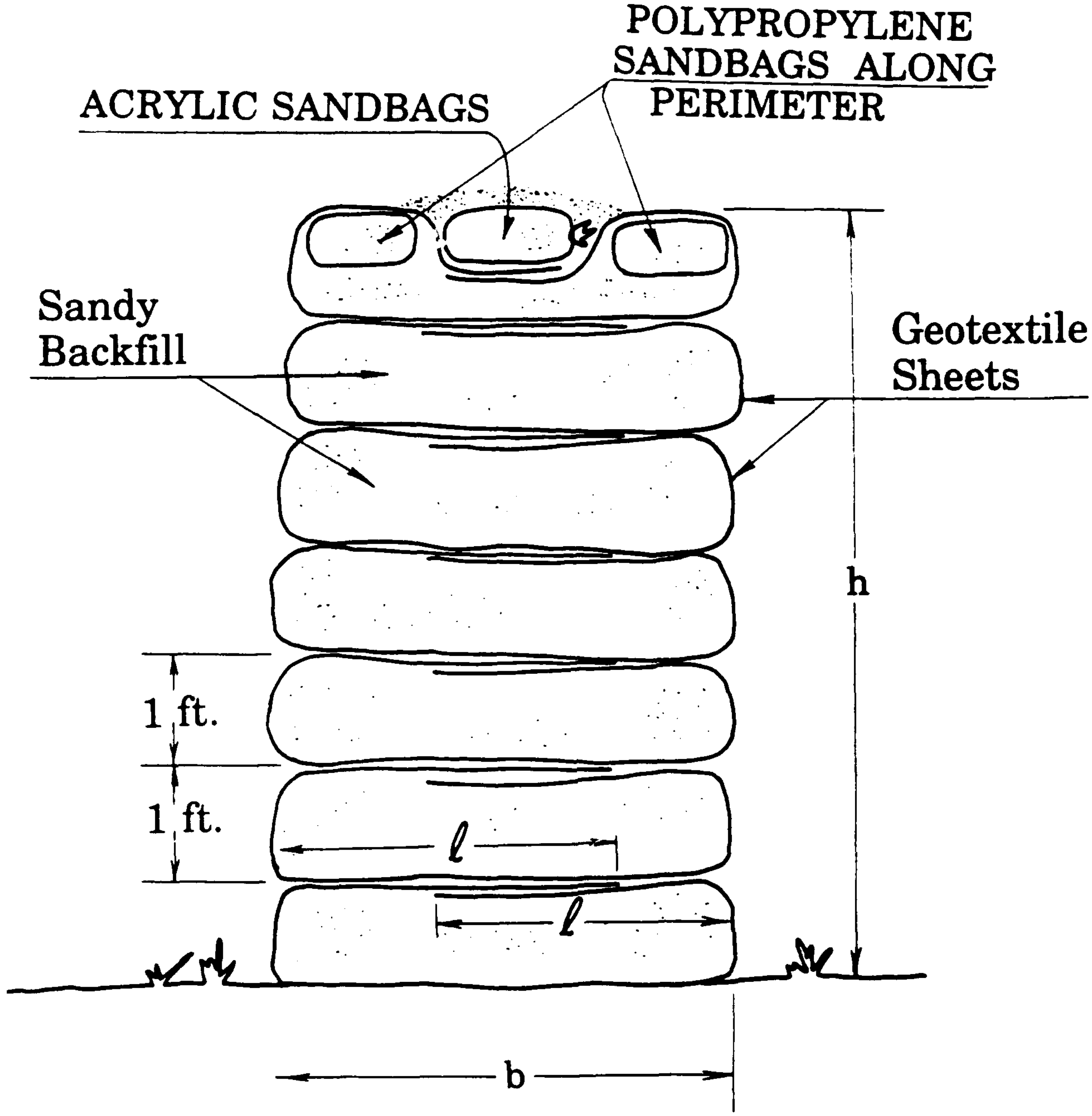


Figure 9. Geosynthetic Earth Filled Walls Last 20 Years And Are 3 Times Cheaper and 8 Times Quicker To Build Than Sand Bag Walls

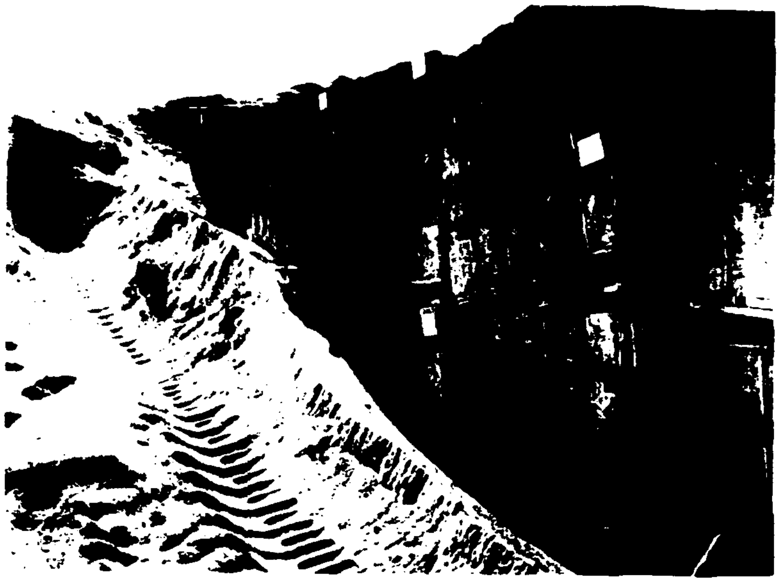


Figure 10a. During Desert Storm, Wind Erosion Made Safe Field Storage Difficult

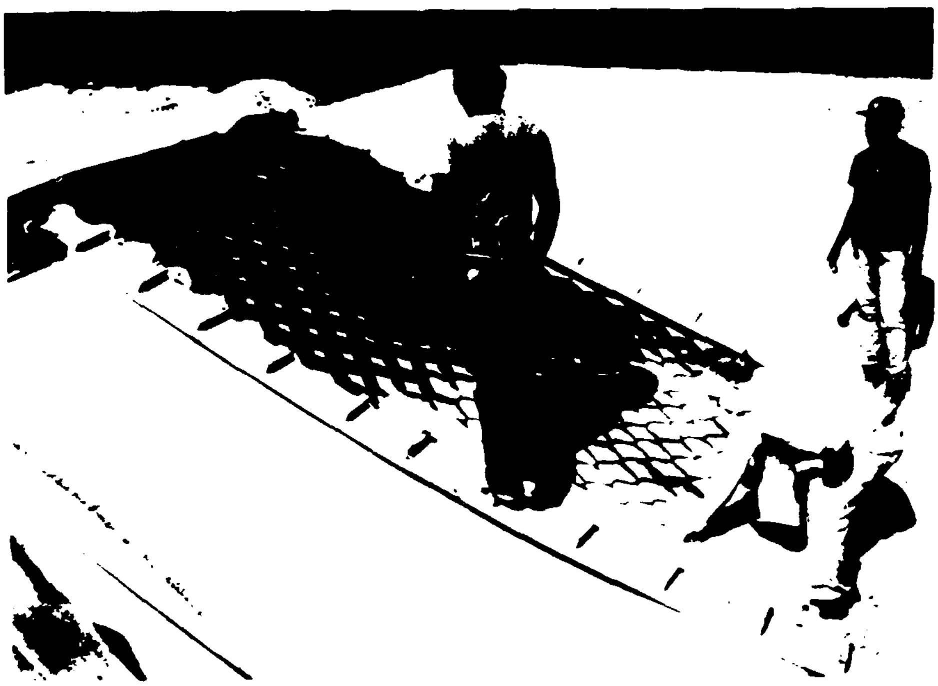


Figure 10b. The Erosion Control Project Identifies Solutions Like This Geoweb to Improve The Stability of Sand Berm Barricades

Simulated Large Scale Propagation Test

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D. Collis

New Mexico Institute of Technology

INTRODUCTION

There exist in Europe, Korea, and elsewhere ammunition magazines under the control of the United States Armed Forces that cannot be utilized to their full capacity because of encroachment of public facilities within the full capacity quantity distance arc. This has led to interest in barriers which could be placed in magazines to prevent the simultaneous detonation of all of the contents. The United States Navy is also interested in barriers to prevent sympathetic detonation in the High Performance Magazine, which is now under development, and barriers between large stocks of ammunition might have other applications, such as in ports where loading and unloading operations are being conducted.

In general, such barriers are beneficial in reducing the quantity distance arc only if the quantitities of ammunition are large. For Hazard Classification 1.1 materials stored in earth-covered magazines, the inhabited building distance remains constant for net explosive weights (NEW) from 1,000 to 50,000 lb. Therefore, subdivision of the stored ammunition has a major benefit only when the total NEW stored is greater than 100,000 lb.

Full-scale testing of candidate designs with this quantity of explosive is extremely expensive, costing millions of dollars per test, and is valid only for the particular type and configuration of munitions tested. Furthermore, there is considerable experience which indicates that the results of small-scale tests cannot be easily extrapolated to full scale. It appears that the mechanism of propagation of detonation can change as the scale of the test increases and as the confinement around the ammunition increases[1,2]. Consequently, the design of such barriers for the prevention of large-scale sympathetic detonation is not easy.

At the request of the Project Manager for Ammunition Logistics (PM AMMOLOG), we have conducted a joint experimental/computational study of how such barriers might be designed. We adopted a extremely conservative design philosophy. We assumed that the barrier must be thick enough to stop all fragments from the detonating (donor) munitions so that the protected (acceptor) munitions would not receive any direct fragment hits. Under these conditions, the biggest threat to the acceptors comes from the impact of the barrier itself. In this paper, we will describe some analysis and an experiment that was conducted to determine the effect of the barrier on the acceptor munitions. The computations are discussed in more detail in a paper by Lawrence and Starkenberg in this symposium.

Description of the Situation To Be Simulated

For the purpose of this study, we assumed that the donor would be a stack of 155-mm or 8-inch projectiles with an NEW of 60,000 lb. Sand was chosen as the barrier material because it is cheap, readily available, and does not produce secondary fragments. Test data indicates that 380 mm of sand will stop all of the fragments from a single 8-inch round[3] (a composition B-loaded 155-mm round produces fragments with only slightly higher velocity and similar mass). Multiple rounds will produce fragments with higher velocity due to the interaction zones between warheads and perhaps due to other effects[4]. For the purpose of this study, we assumed that the barrier must be at least 500 mm thick, and preferably 1 m thick, to stop all fragments.

To determine the velocity which would be imparted to the barrier by the detonation of the donors, Lawrence and Starkenberg ran a series of calculations which are described in more detail in another paper in this symposium. To minimize computational time, the magazine was represented as a cylindrical structure, 8 m in diameter (interior), 24.4 m long (interior), with 200-mm concrete walls surrounded by 610 mm of sand (roughly speaking, this structure can be thought of as two identical magazines joined at the floor). The barrier was a cylindrical "plug," 6.8 m in diameter, in the center of the magazine. The diameter of the barrier permitted some gas flow over the "top" of the barrier. The thickness of the barrier was varied, and, on some calculations, some additional vent area was provided through the barrier. The donor charge was a solid block of TNT with a mass of 56.5 Mg (124,000 lb) (twice the mass in a single "real" magazine), and it simulated the explosive in 976 pallets of M107 rounds (488 pallets in each half of the cylindrical magazine). The storage volume of the M107 projectile is such that the center of the stack could be located as close as 3.7 m from the edge of the barrier or as much as 8.5 m. The spacing was varied in the calculations.

The calculations indicated that a 1-meter-thick sand barrier located 5 m (center to center separation) from the TNT charge would obtain a velocity of 514 m/s (this value was obtained by averaging several computational stations in the wall). For the same conditions, a 0.5-m-thick sand barrier would obtain a velocity of 867 m/s, and a 2.0-m-thick barrier would obtain a velocity of 290 m/s. When the center to center spacing from the barrier was increased to 10 m, the velocity for the 1-m-thick barrier dropped to 443 m/s. Small amounts of venting in the barrier had only a small effect on the barrier velocity.

We chose to simulate the case of a 1-meter-thick barrier with a center to center separation between the barrier and the explosive stack of 10 m. It appeared that significantly thinner barriers could obtain velocities sufficient to cause prompt shock initiation of the acceptors, and thinner barriers might also have a problem in stopping all fragments. In retrospect, a thicker barrier may have been a better choice, as will be seen below.

Description of the Test

To see the effect of such a barrier on the acceptor munitions, we designed an experiment which was intended to project a 1-meter-thick sand barrier at M107 projectiles at a velocity of about 400 m/s. The experimental arrangement is shown in Figures 1 and 2. A 380-mm-thick layer of ANFO (ammonium nitrate with 6 % fuel oil) explosive was sandwiched between two 1-m-thick layers of sand. The sand and explosive layers were 1.83 m high and 3 m wide. The detonation of the ANFO drove the sand barriers into two test chambers which were 2 m deep and had the same height and width as the sand barriers. One of the test chambers contained two pallets of Composition B-loaded M107 projectiles, and the other contained two pallets of instrumented, inert loaded M107s. The entire structure was buried below ground level at a test site at the New Mexico Institute of Technology.

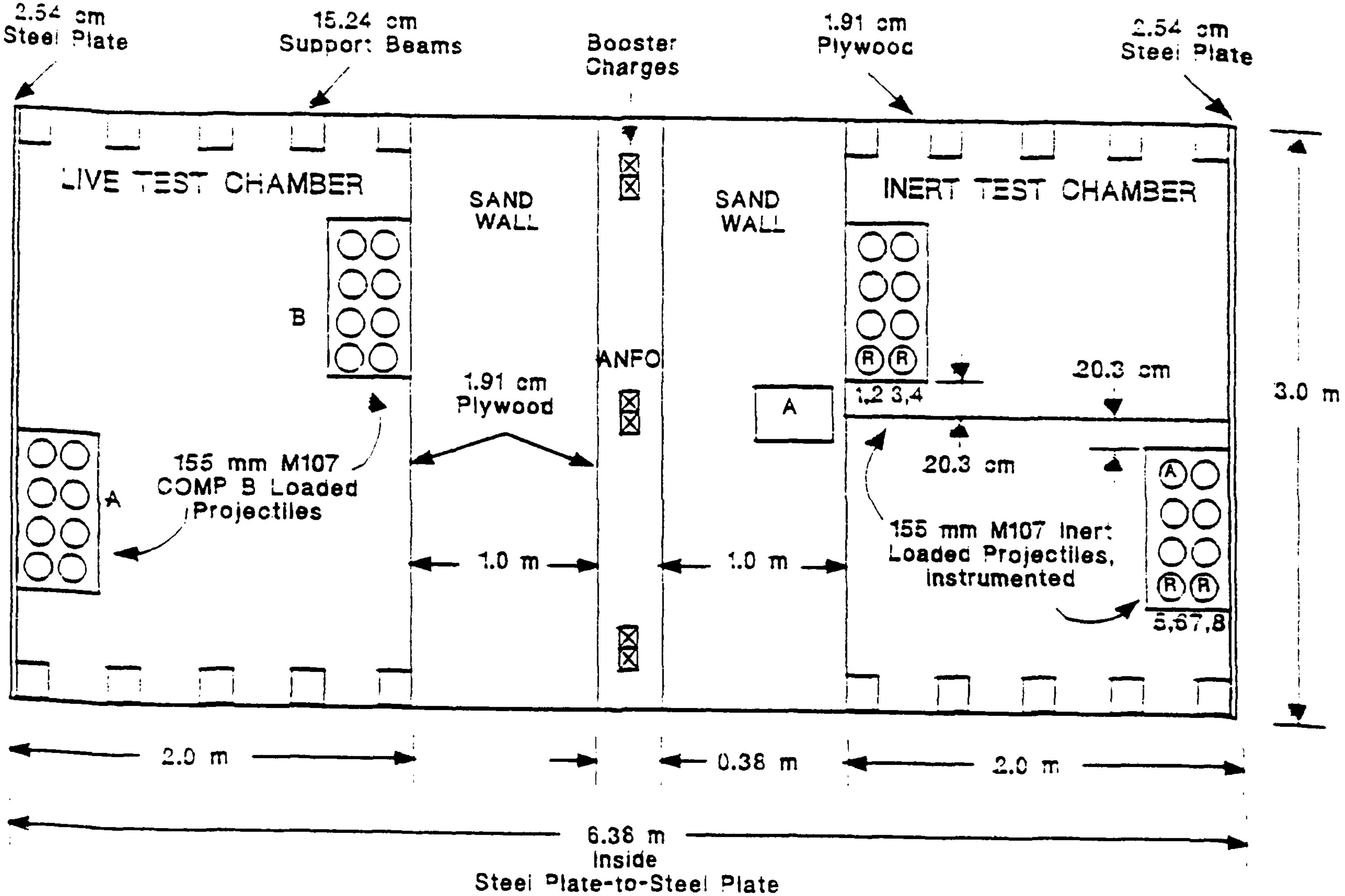

Figure 1. Top View of Experimental Setup.

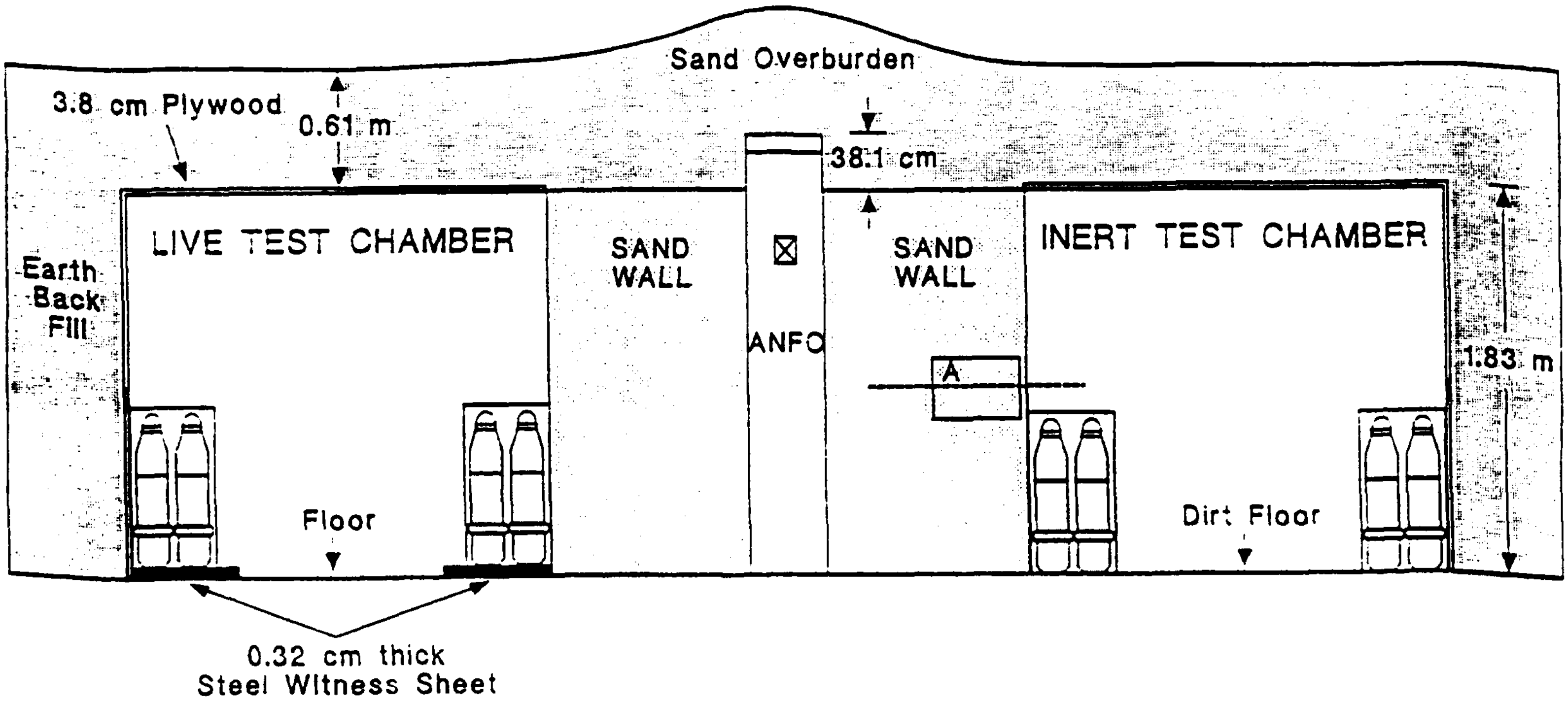

Figure 2. Side View of Experimental Setup.

A wooden structure was built to hold the explosive and the sand barriers and to keep earth from entering the test chambers. The sides of the sand barriers were constructed of two pieces of 9.5-mm plywood which were laminated together with wood glue to give a 19.1-mm-thick wood support. The opposite sides of the barrier were attached using multiple Kevlar straps to keep the walls from bowing as the sand was added. Figure 3 is a photograph of the structure that held the sand barriers and the explosive layer before the sand and explosive were loaded. Standard construction sand was used in the barriers and contained less than 5% rock. Any rocks which were present in the sand measured less than 12.7 mm in diameter. The sides of the test chambers were made of 19.1-mm-thick plywood supported by 152 × 152-mm wooden beams. The roof was a double thickness of 19.1-mm plywood, also supported by 152 × 152-mm wooden beams. Figure 4 shows one of the test chambers before it was buried. The rear wall of each test chamber was covered with a 25.4-mm-thick mild steel plate. The entire structure was buried in the ground, and the roof was covered with 610 mm of sand.

In the live-test chamber, one pallet of Composition B-loaded M107 projectiles was located immediately adjacent to the sand barrier and slightly off the center line as shown in Figure 1. The pallet was situated so that four rounds were against the sand barrier. The edge of the pallet was flush with the plywood retaining walls, which allows about 25 mm of free space between the plywood and the projectiles. Another pallet was located adjacent to the rear steel wall on the other side of the center line. A 3.2-mm steel witness plate was placed under each pallet, and the steel back wall of the test chamber also served as a witness plate.

The inert chamber was a mirror image of the live chamber, but the pallets contained inert rounds. Four of the acceptor rounds were instrumented with a total of eight carbon resistor gages[5]. The rounds that contained the resistor gages are marked with an "R" in Figure 1. One of the rounds was instrumented with a self-recording accelerometer[6] that was provided by personnel from the Waterways Experimental Station. It is marked with an "A" in Figure 1. A similar accelerometer was placed in the sand wall, centered on the face of the wall adjacent to the test chamber.

The ANFO was detonated using six 5-lb-charges of Thermex 200. The total weight of the ANFO was 2,268 kg.

Simulations of the Test

Lawrence and Starkenberg (see their paper in this symposium) ran simulations of the test using the HULL code. As before, they used cylindrical symmetry to save computational time. The sand wall was represented by a cylinder 4 m in diameter and 1 m thick. The ANFO was also a 4-m-diameter cylinder initiated at a point on the center line. Since the diameter was somewhat greater than the actual lateral dimensions of the experment, the computed barrier velocities are probably a little too high. The plywood forms which held the sand were not included in the calculations. The first simulations were solely for the purpose of determining the wall velocity as a function of the thickness of the ANFO. The calculations indicated that the first shock through the barrier accelerates the barrier to about two thirds of its final velocity, and the barrier continues to accelerate until it reaches the rear wall. With 400 mm of ANFO, the maximium velocity was 417 m/s (averaged over several stations 100 mm from the free surface of the barrier). With 300 mm of ANFO, the maximum velocity was 330 m/s. In the test, 380 mm of ANFO were used and interpolation of the computed results gives a predicted final velocity of about 400 m/s for the test condition. In the real test, the velocity was probably somewhat lower for reasons already stated. In another calculation of this type (not reported in the accompanying Lawrence and Starkenberg paper), we looked for evidence that the surface of the sand barrier might be "spalling" and moving off with a higher velocity than the rest of the wall. To see if this was so, the velocity was determined at a point 30 mm from the surface (instead of 100 mm). The result indicated that the surface was not moving

appreciably faster than the interior. The computed pressure in the sand supported this conclusion. It indicated that the shock pressure decreased markedly as the shock moved across the sand barrier, from about 64 kbar at the explosive-sand interface to about 7 kbar at the air-sand interface.

A second set of simulations was run to determine the pressure in the acceptors due to the impact of the sand. In this case, a 2-D plane-strain simulation was used, so the acceptor was represented as an infinitely long cylinder with constant wall thickness. One calculation simulated the impact of the sand on the rounds which were against the rear steel wall. In this case, the rounds are first shocked and then crushed by the impact. For this calculation, the wall was given a velocity of 360 m/s, and the calculation was started at the time the wall impacts the rounds. The maximum computed pressure in the rounds was 3.5 kbar, well below the pressures usually associated with shock initiation in undamaged composition B. A possibly significant feature of the calculations is that the pressure in the explosive in the acceptor round showed several strong oscillations with a period of about 18 μs. Because of the complicated pressure-time history (see Lawrence and Starkenberg), the duration of the shock pressure cannot be determined in an unambiguous fashion. Near the front of the acceptor (but in the explosive), the pressure dropped almost to zero after about 18 μs, but this was followed by further oscillations. At points closer to the interior of the acceptor, the oscillations were weaker, and it is more difficult to specify a shock duration.

Another simulation was run to determine the pressure in the acceptors that were near the sand wall. This calculation (not reported in the accompanying paper by Lawrence and Starkenberg) also used the plane-strain geometry, but it included the detonation of the explosive (along a line at the bottom of the ANFO) and the acceleration of the barrier. A 25-mm air gap was included between the edge of the wall and the acceptors, but the plywood was ignored. In this case, the impact of the sand produced a peak pressure in the acceptor of about 3.5 kbar, about the same as the pressure in the rounds against the rear wall. However, in this case, there was a second pressure pulse when the acceptor rounds hit the rear steel wall. The peak pressure for the second pulse was about 3.8 kbar, slightly higher than for the first pulse.

TEST RESULTS

A crater measuring approximately 21.3 m × 10.7 m × 5.5 m deep was created. The rear steel walls of the test chambers were destroyed, and only portions of the bottom section were recovered. No other portion of the test chamber was recovered. Several of the inert instrumented projectiles were recovered. These were severely cracked, and several were broken into multiple pieces. The bottom rear steel wall recovered in the inert chamber was severely deformed, but contained no perforations. Figures 5, 6, and 7 show the recovered portion of the rear wall from the inert chamber, and inert projectiles recovered after the test. Note the severe damage the projectiles experienced. None of the recovered projectiles have the nose plug in place, and all are badly dented or split open. The inert fill is seen to be extruded from the nose opening.

There was substantial evidence that the live acceptors detonated. Minimal projectile fragments were recovered: one base fragment and portions of side fragments. The steel witness sheets located under the live projectile pallets were severely deformed and torn into multiple pieces. No live acceptor projectiles were recovered intact. There were also multiple fragment perforations in the rear steel wall adjacent to the live acceptor pallet (but the steel wall on the inert side was not perforated). These perforations appear to have been made by a round which detonated at some distance from the wall. Thus, it appears that the rounds near the sand wall may have detonated, and they probably detonated before they impacted the rear wall.

Figure 3. Photograph of the Structure Holding the Sand Barrier and the Explosive.

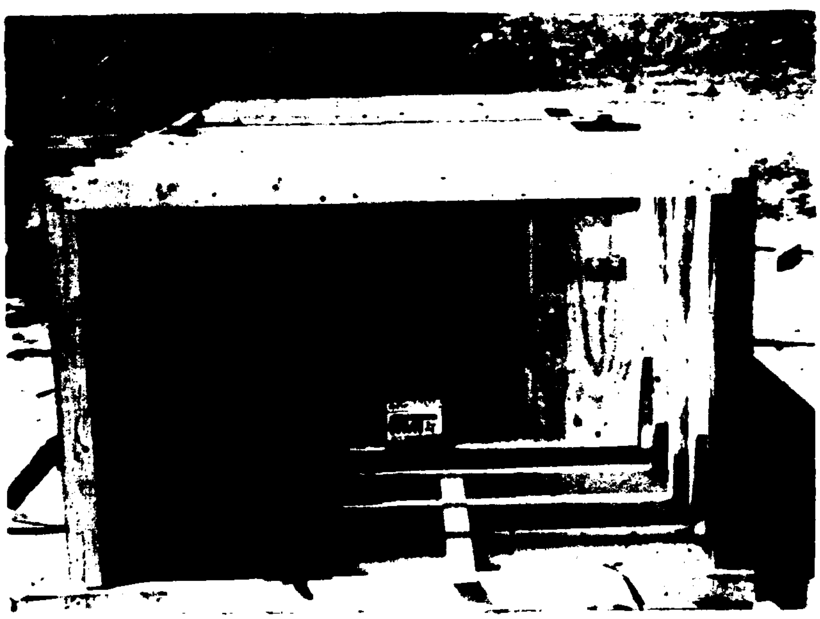

Figure 4. Photograph of the Structure Surrounding the Test Chambers.

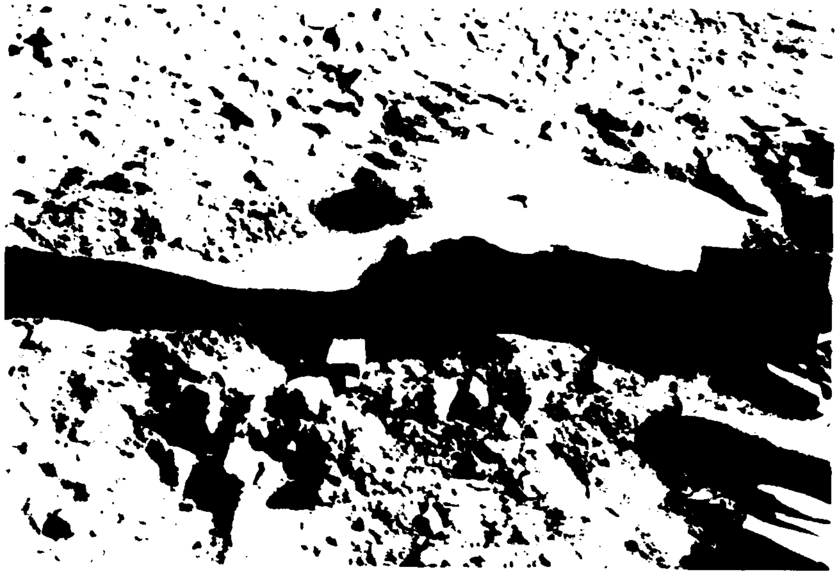

Figure 5. After Test Photograph of a Portion of the Steel Wall on the Inert Side.

Figure 6. After Test Photograph of the Inert Rounds.

Figure 7. After Test Photograph of the Inert Rounds.

We believe all of the rounds detonated, but there is some question about this because some large fragments from the live projectiles were found. However, it is known that large fragments can be produced when multiple rounds in close proximity detonate[6]. Our conclusion that all rounds detonated is based on the absense of any base fragments and the damage to the witness plate that was under the rounds. Figures 8, 9, and 10 show the recovered portion of the rear wall from the live chamber, some of the larger fragments from the live projectiles after the test, and the steel witness plate that was under the live projectiles.

The accelerometer in the sand wall was not recovered. The one in the inert pallet was recovered, but it had been destroyed by the event, and it was not possible to extract any data. Records were obtained from six of the eight resistance gages. However, after analysis, we have concluded that the records were not meaningful. It appears that the gage leads broke early in the event and the apparent signal observed later was caused by shorting of the leads.

Discussion

The detonation of the acceptor rounds was somewhat of a surprise. The predicted shock pressure in the rounds was less than 4 kbar, well below the pressures usually associated with initiation of detonation in composition B. In fact, in aquarium tests, Liddiard[7] found that 4 kbar was the threshold point for detecting shock-induced burning (not detonation) in Composition B. One might also analyze these results in terms of the "critical energy" criterion[8] for initiation. We are very dubious about the applicability of this criterion to the present circumstance, but we considered it anyhow. Reference 8 gives the critical energy of Composition B as 1,850 kj/m^2. If we take the pulse duration as 18 µs, a pressure of 7.0 kbar is required for initiation of detonation. However, if the pulse duration were taken as 100 µs, which might

Figure 8. After Test Photograph of a Portion of the Steel Wall on the Live Side.

Figure 9. Aftger Test Photograph of the Larger Fragments from the Live Rounds.

Figure 10. After Test Photograph of the Witness Plate Under the Live Rounds.

be justified on the basis of the Lawrence and Starkenberg calculations, the critical pressure would be 3.0 kbar. This is in the range of the computed maximum pressures, but it is higher than the average pressure over 100 µs (see Lawrence and Starkenberg).

We can only speculate on why detonation occurred. A prime suspect in our minds is the fact that the acceptors saw multiple pressure pulses. This was true in two respects. First, there were strong oscillations associated with the impact of the sand wall on the rounds. Second, for the rounds adjacent to the sand wall, there was a second shock when they hit the rear wall. As has often been discussed in the explosives literature, an earlier event can damage the explosive and sensitize it to a later event. If the rounds detonated while they were still some distance from the rear wall, as the evidence appears to indicate, the second effect is ruled out, but the first is a strong possibility.

Another possible source of initiation to violent reaction of the live projectiles is the crushing that occurred as evidenced by the recovered inert projectiles. Although this is a known mechanism, the critical parameters governing this mechanism are not yet well understood, particularly for heavily cased explosives. This may not be the mechanism that produced the fragments that perforated the rear wall, but there may well have been different mechanisms for different projectiles depending on their location.

The significant result of this study is that, in situations such as this, detonation may occur with stimuli much weaker than one might expect based on small scale data. In the present case, it appears that a shock of 3.5 kbar was sufficient to cause detonation (although several oscillations may have been involved).

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A SAFER METHOD OF STORING AMMUNITION IN A CONEX CONTAINER

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ABSTRACT

Many of the explosively loaded munitions in the inventory today are packaged and stored in such a manner that they respond en masse to an accidental initiation. As a result, a mass detonation of all the munitions in the storage area can occur. Techniques can be used to control the sympathetic response of munitions through the use of antifratricide devices, such as buffers, deflectors, and spoilers. All three types of antifratricide devices were employed in development of a storage configuration for boxed 4.2-inch mortar ammunition which limited the event to a single box of mortar rounds. The fires that were encountered, due mainly to splintered wood, had to be eliminated in order to prevent late-time cook-offs of munitions. Incorporation of fire extinguishing techniques into the antifratricide devices eliminated fires and late-time cook-off problems. The danger area associated with a Conex was reduced by over 98% by implementing antifratricide, fire extinguishing, and sandbagging measures.

INTRODUCTION

Where ammunition storage facilities are not adequate for the amount of ammunition on hand, Conex containers are often used for storage. A typical packing density in a Conex used to store 4.2-inch mortar rounds might be 24 boxes of M329A2 Composition B (Comp B) rounds, 2 rounds per box, and 18 boxes of M335 illuminating rounds, 2 rounds per box. The high explosive (HE) rounds each contain 5.5 lb (2.5 kg) of Comp B. Since there are two rounds per box (packed so that both warheads are at the same end of the box), any detonation would involve at least 11 lb (5 kg) of HE, even if only one box detonated. If mass detonation should occur, 264 lb (120 kg) of HE would be involved. Mass detonation of the M329A2 rounds is to be expected, since these rounds are assigned to the 1.1 hazard class division.[1] The danger radius around the Conex, due to fragments, in case of a detonation, is 1,250 ft (as assigned by the Department of Defense Explosive Safety Board [DDESB]).[2,3] Any measures which could be taken to reduce the 1,250-ft hazard radius would obviously be highly desirable.

The task of preventing mass detonation of the M329A2 mortar rounds in a Conex, given the detonation of one box, was assigned to the U.S. Army Ballistic Research Laboratory (BRL). The experiments that led to the design of the storage module for the 4.2-inch mortar ammunition were described in detail in a paper given at the Australian DOD Explosives Safety Seminar held in 1987 in Canberra, Australia.[4] A wooden module which incorporated techniques of buffering, deflecting, and spoiling was designed and shown to be capable of limiting the initial event to one box of HE rounds. However, the accompanying fire, due mainly to splintered wood, caused late-time cook-offs. A description of the fire extinguishing techniques used to eliminate the wood fire is given in this paper.

FIRE SUPPRESSION

The approach to the fire problem was to adopt a passive system rather than an active system. In that way, there would be no need for any electrical or mechanical devices which might require periodic maintenance or testing. The wooden modules (the key element of the antifratricide success) were retained, albeit with dimensions slightly modified to maximize the amount of fire extinguishing material which could be incorporated into the free volume of the modules. The extinguishing material was in close proximity to the HE warheads. If a warhead detonated, the containers of fire extinguishing material would rupture, and the material would be released throughout the Conex, but, more importantly, at the detonation site. The major problem foreseen was that this would severely limit venting of the explosive gases. Venting was an important feature of the original module concept. A schematic of the final design of the module is given in Figure 1. A schematic of a module with containers of fire suppression material in place is given in Figure 2.

TESTS AT NMIMT

Plans for the modules were sent to the New Mexico Institute of Mining and Technology, (NMIMT) Socorro, NM, so that the modules could be constructed on site. For each test, a Conex was put in place and sandbags, 30–36-inches deep, were placed around three sides from the ground to the roof. There were no sandbags on the front (door) side of the Conex. Two layers of sandbags (15–18-inches high) were placed on the roof. The doors were closed and secured before each test. No wall was used in front of any Conex for these tests.

The basic arrangement of modules in the Conex is shown in Figure 3. Most tests were conducted with just the HE mortars in the Conex, although two tests (full-up) contained both HE and illuminating mortars. The results of the tests at Socorro are given in Table 1. Only two tests were done with Purple K fire extinguishing powder. The first was a success with no cook-offs. The second test was unsuccessful in that a fire occurred, causing cook-offs. At that point in time, a decision was made to replace the powder with a liquid fire extinguishing agent. Only later, upon close examination of videos, was it discovered that in the second test with Purple K powder, the modules had been stacked improperly. As a result, there was a box of Comp B mortars directly over the box which served as the donor. In all probability, at least four Comp B warheads detonated in the initial event. While this larger than desired initial event may have contributed to the failure of the second test with Purple K, no further work was done with powdered fire extinguishing agent.

In the warhead detonation tests involving the passive liquid fire extinguishing approach, all tests were successful. Detonation was limited to the two rounds deliberately detonated. There were no subsequent fires and no cook-offs.

In the single case involving a different scenario, that of a rocket propelled grenade (RPG) attack on illuminating rounds stored in the same Conex as HE rounds, there was a fire and cook-offs of the HE-containing rounds. There were many differences between this test and the others. In this test, a viper shaped charge warhead was fired from outside the Conex, through a door aimed at the region of the boxes of illuminating rounds. These illuminating rounds were not in modules and they had no fire extinguishing agent close by. The 18 boxes of 2 each illuminating rounds were simply stacked (3 boxes wide by 6 boxes high) in the Conex across from the modules of HE-containing rounds. For this last test at NMIMT, no Comp B-containing mortar rounds were available; therefore, TNT-containing rounds were used. The boxes of TNT rounds were approximately 6 inches longer than the boxes of Comp B mortar rounds. The TNT mortar boxes extended beyond the modules into the center of the Conex. There was no fire protection around the TNT rounds for the last 6 inches.

When the viper warhead was fired through the door of the Conex, the door remained closed. Clouds of white smoke from the burning illuminating round(s) came out of the Conex. The Conex was intact. There was a subsequent apparent cook-off of illuminating rounds, as clouds of white smoke came from the still-intact Conex. At 61.5 minutes after the firing of the

Table 1. Summary of the Eight Conex Tests Performed at Socorro, NM

Test Number	Munitions	Fire Ext.	Initiation	Results
1	48 Comp B 4.2-inch mortars unfuzed	48 jugs Purple K powder 1,137 lb	Detonation of 2 rounds 11 lb Comp B total	46 rounds recovered no cook-offs
2	48 Comp B 4.2-inch mortars unfuzed	48 jugs Purple K powder 1,137 lb	Detonation of more than 2 rounds	Many cook-offs
3	48 Comp B 4.2-inch mortars unfuzed	48 jugs water plus AFFF plus thickener (did not mix) 545 qt	Detonation of 2 rounds 11 lb Comp B total	46 rounds recovered no cook-offs
4	48 Comp B 4.2-inch mortars unfuzed	48 jugs water plus thickener (did not mix) 545 qt	Detonation of 2 rounds 11 lb Comp B total	46 rounds recovered no cook-offs
5	48 Comp B 4.2-inch mortars unfuzed	144 jugs water plus AFFF plus propylene glycol 614 qt	Detonation of 2 rounds 11 lb Comp B total	46 rounds recovered no cook-offs
6	46 Comp B 4.2-inch mortars unfuzed plus 2 sand-filled tubes	144 jugs water plus AFFF plus propylene glycol 614 qt	Detonation of 2 Comp B rounds 11 lb total	44 rounds recovered no cook-off
7	18 Comp B 4.2-inch mortars unfuzed plus 30 TNT 4.2-inch mortars unfuzed plus 36 illuminating rounds	144 jugs water plus AFFF plus propylene glycol 614 qt	Detonation of 2 Comp B rounds 11 lb total	16 Comp B 30 TNT 36 illuminating rounds recovered no cook-offs
8	48 TNT 4.2-inch mortars unfuzed plus 36 illuminating rounds	144 jugs water plus AFFF plus propylene glycol 614 qt	Viper through Conex door into illuminating rounds	23 min to first illuminating round cook-off 61.5 min to first TNT round cook-off many rounds cooked off

shaped charge, there was a detonation which destroyed the Conex. This detonation did not quench the fire. There were many subsequent cook-offs of TNT rounds.

It had been expected that when the shaped charge jet struck the boxes of illuminating rounds, there would be a fire, since there were no modules of fire extinguishing agents packed with the illuminating rounds. A cook-off of a box of HE rounds had also been expected, but the subsequent cook-offs of more HE rounds had not been expected. A possible explanation is that when the first box of TNT rounds detonated, it did not cause the release of enough liquid fire extinguishing agent to quench the fire. Since the last 6 inches of the TNT boxes were not surrounded by fire extinguishing agent, close-by boxes of TNT rounds were shattered open without the release of enough agent to completely wet the splintered wood. It is believed by the authors that had modules 6 inches longer been used, containing the maximum amount of liquid fire extinguishing agent, only one box of TNT rounds would have cooked-off. However, no further tests were possible to prove or disprove this belief.

An all-weather liquid formulation was devised which proved successful in immediately quenching the reaction after the initial detonation of two Comp B warheads. The arrangement was capable of providing protection even when illuminating rounds (without any modules) were present. The liquid formation used was the following:

- 50% by volume propylene glycol
- 25% by volume water
- 25% by volume aqueous film-forming foam (AFFF) NSN No. 4210-01-056-8343

PROOF TESTS AT UTAH TEST AND TRAINING RANGE

Three tests of the 4.2-inch mortar Conex storage container were conducted at the Utah Test and Training Range by Air Force and civilian personnel. The test configuration had five plastic containers of the all-weather, liquid fire extinguishing agent per module, as had been proved successful in the Socorro tests against detonation of two M329A2 Comp B warheads. All three tests involved both HE and illuminating rounds. A schematic of the stacking arrangement for these tests is given in Figure 4.

In order to keep the fragments to a minimum, the Conex container was sandbagged on the three walls and on the roof. To minimize the fragments from the doors of the Conex, a sand-filled wall made from angle iron with a sheet metal skin was place 12 ft in front of the doors. For the first test, the wall was 16-ft long, 8-ft high, and 2-ft thick. The wall was made from two 8-ft by 8-ft by 2-ft sections placed in front of the doors. The two 8-ft sections were centered in front of the doors leaving a seam also centered in front of the doors. In the first test, the blast from the detonation moved the two sections and opened them at the seam. It was then decided to use three sections for the second and third tests for a 24-ft by 8-ft by 2-ft wall. The wall location for all three tests in reference to the Conex (not to scale) can be seen in Figure 5.

All three tests were successful. There were no fires and no cook-offs. There was only one missing round in the tests and it was believed to have survived the event, just never found. The only detonation was the initial event. Since there were two warheads per box, the initial event had to involve an even number of rounds. The one missing round may have been buried in the Utah sand.

Combining all tests, the farthest fragment in front of the doors (±15°) was found at 308 ft. The farthest fragment in the 15–345° zone was at 128 ft and the second farthest was at 98 ft. The fragment danger radius was reduced from the 1,250-ft radius[3] associated with an unprotected Conex to a 100-ft radius with a 30° arc out to 310 ft. This calculates to a reduction in the danger zone from 4,908,738 ft^2 to approximately 53,957 ft^2, as can be seen in Figure 6. This is only 1.1% of the original danger zone. The details of these three tests are given in Tables 2, 3, and 4 and Figures 7, 8, and 9.

CONCLUSIONS

The successful design of a storage system for M329A2 Comp B-loaded 4.2-inch mortar rounds has been accomplished. The design provides protection against mass detonation of the rounds and protection against any subsequent fire, given the spontaneous detonation of one box of two rounds. This provides a meaningful reduction in hazards associated with storage of these rounds. The design depends on antifratricide protection due to the use of modules and specified stacking order, the use of an all-weather fire extinguishing agent, and

Table 2. 4.2-inch Mortar Test Fragment Chart, Test 1 at Utah Test and Training Range

Distance (ft)	Radial (°)	Description
17.0	0	HE Round
17.5	0	HE Round
19.0	0	HE Round
24.0	0	HE Round
25.5	0	HE Round
28.0	0	Primer
42.3	0	Charge
44.0	0	HE Round
47.5	0	HE Round[a]
48.0	0	HE Round[b]
20.0	45	HE Round
18.0	150	HE Round
28.0	150	HE Round
40.0	150	HE Round[c]
3.5	180	HE Round
1.0	185	HE Round
1.0	185	HE Round
12.5	190	HE Round
32.0	200	HE Round[d]
9.5	225	Primer
3.8	225	HE Round
6.5	280	HE Round
30.0	315	HE Round
19.0	330	HE Round

[a] 2nd farthest fragment 15° +/–
[b] farthest fragment 15° +/–
[c] farthest fragment 15–345°
[d] 2nd farthest fragment 15–345°

Table 3. 4.2-inch Mortar Test Fragment Chart, Test 2 at Utah Test and Training Range

Fragment No.	Distance (ft)	Radial (°)	Description
1	88.0	0	HE Round
2	74.0	30	Wood
3	89.0	83	Booster
4	95.0	90	Wood[a]
5	70.0	95	Wood
6	98.0	108	Wood[b]
7	52.0	180	HE Round
8	62.0	181	Booster
9	63.0	181	HE Round
10	47.0	155	Booster
11	85.0	299	Steel
12	11.0	0	HE Round
13	11.0	0	HE Round
14	6.0	0	Illum. Round
15	7.0	90	HE Round
16	5.0	110	HE Round
17	14.0	110	HE Round
18	19.0	165	HE Round
19	35.0	175	HE Round
20	23.0	190	HE Round
21	17.0	195	HE Round
22	7.0	195	HE Round
23	4.5	210	HE Round
24	28.0	210	HE Round
25	260.0	8	HE Round
26	288.0	3	HE Round[c]
27	308.0	7	HE Round[d]

[a] 2nd farthest fragment 15–345°
[b] farthest fragment 15–345°
[c] 2nd farthest fragment 15° +/–
[d] farthest fragment 15° +/–

Table 4. 4.2-inch Mortar Test Fragment Chart, Test 3 at Utah Test and Training Range

Fragment No.	Distance (ft)	Radial (°)	Description
1	79	35	Metal Door
2	62	40	Wood
3	78	90	Wood
4	84	90	Wood[a]
5	126	95	Metal Roof[a]
6	69	270	Metal
7	73	5	Wood
8	197	5	HE Round
9	213	8	HE Round[b]
10	233	10	HE Round[b]
11	147	355	Metal
12	107	345	Metal

[a] 2 farthest fragments 15–345°
[b] 2 farthest fragments 15° +/–

Note: All frags and rounds within 50 ft are not listed.

sandbagging of the Conex. The danger zone around the Conexes was reduced to only 1.1% of the original area. This reduction applies only if no other type of round (illuminating, phosphorous, etc.) is stored with the HE rounds.

If HE rounds other than Comp B type are to be protected, the modules should be made of the proper size to fit the boxes of rounds. Thus, if TNT mortar rounds are to be stored in a Conex, the modules for these rounds should be 6 inches longer than the modules used with Comp B rounds. In any event, the modules should contain the maximum amount of liquid fire extinguishing agent that can be put into the modules.

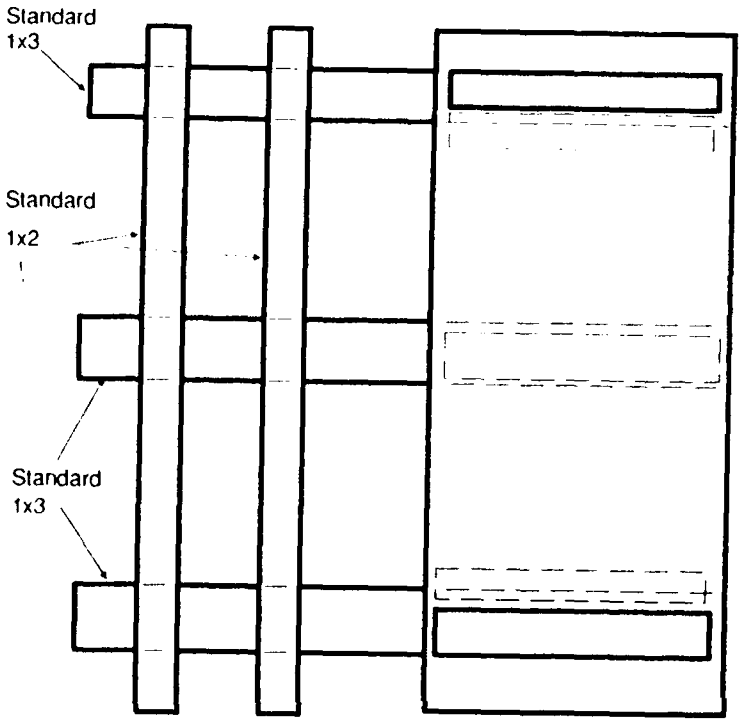
REFERENCES

[1] U.S. Army Ammunition Center and School. "Hazard Classification of U.S. Military Explosives and Hazardous Munitions." U.S. Army Armament, Munitions, and Chemical Command, Rock Island, IL, November 1983.

[2] AR 385-64. Ammunition and Explosive Safety Standards.

[3] Assistant Secretary of Defense. DOD Ammunition and Explosive Safety Standard. DOD 6055.9-STD. Manpower, Installations, and Logistics, Washington DC, 1984.

[4] Watson, Jerry L. "Controlling the Sympathetic Response of Mass-Detonating Munitions," Proceedings of the 2nd Australian Department of Defense Explosives Safety Seminar, 30 Nov–1 Dec 1987, Canberra, Australia.

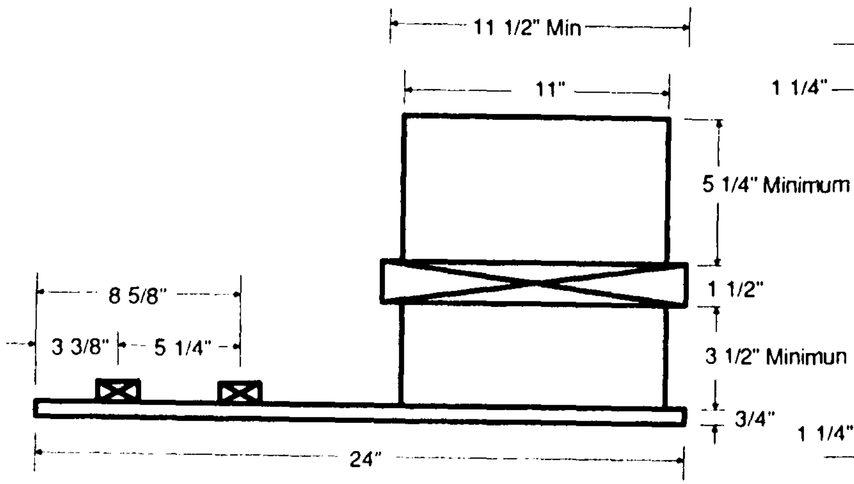


Details of 4.2 inch Mortar Stacking Module

Indicates End Grain

All dimensions marked Minimum (Min) must be at least that dimension in order for the fire suppressent containers to fit properly. An oversized tolerance of + 1/4" is allowed

To nail 2x4's to 2x12's use 16D common nails
For all else use 4D common nails



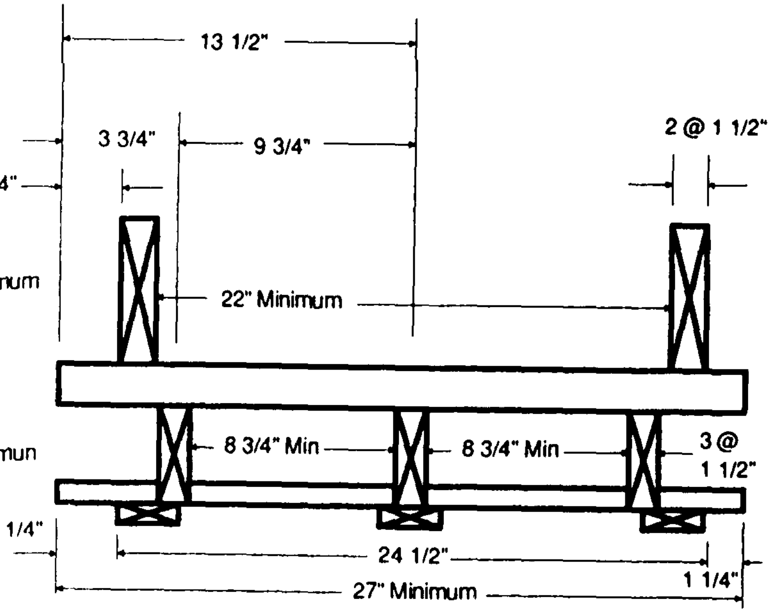


Figure 1. Final Version of the Stacking Module.

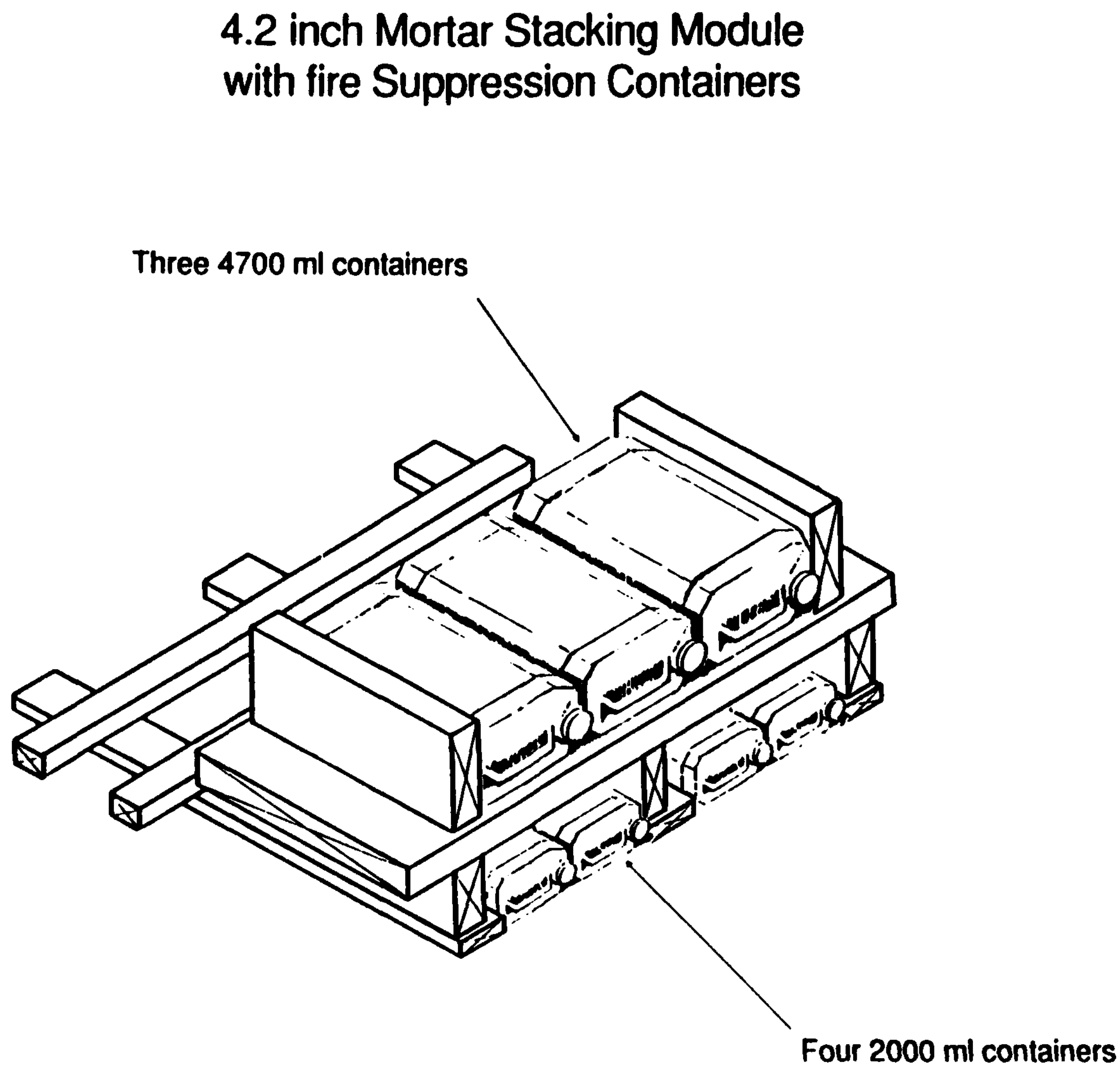


Figure 2. Stacking Module With Fire Suppression Containers.

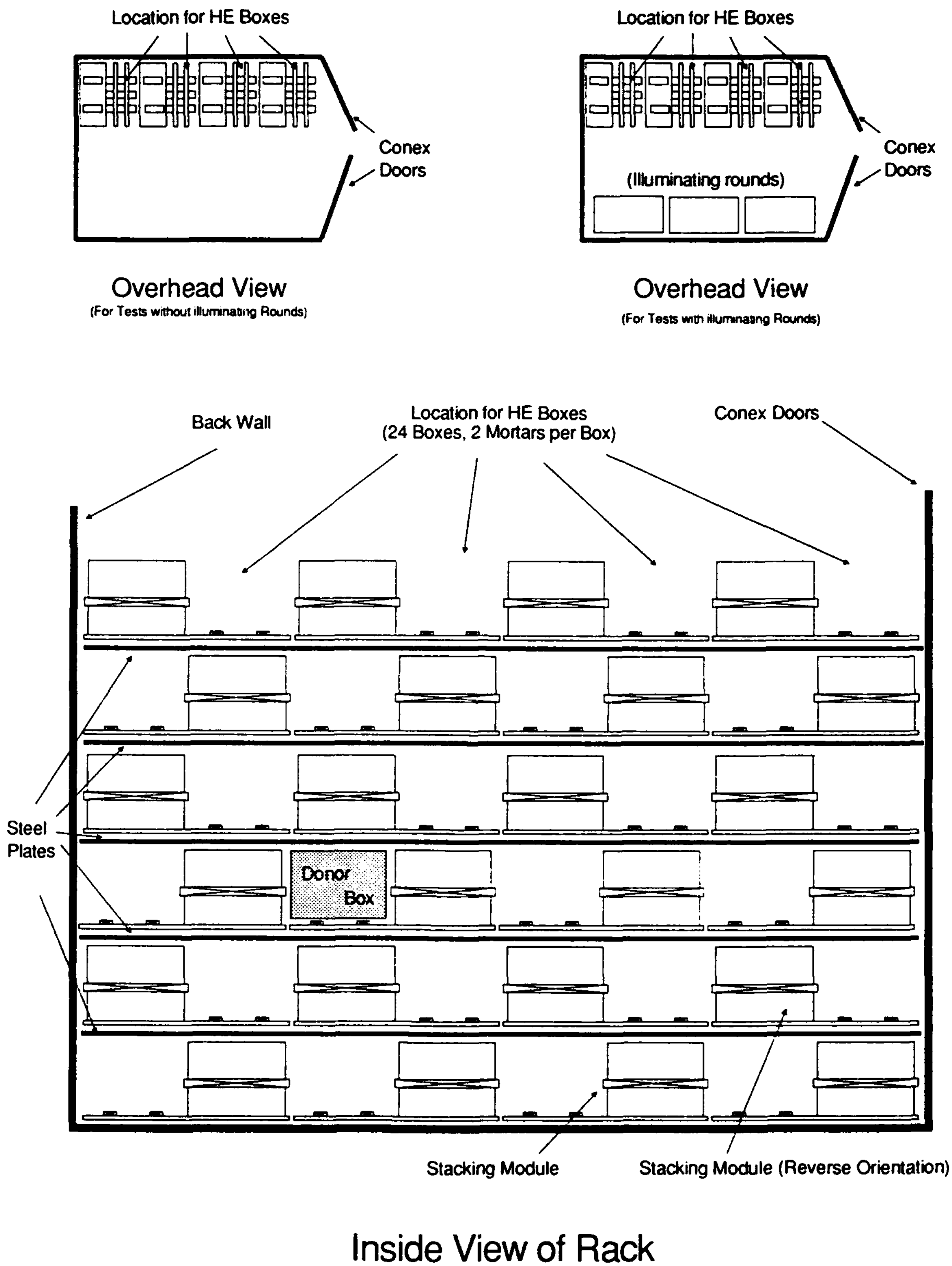
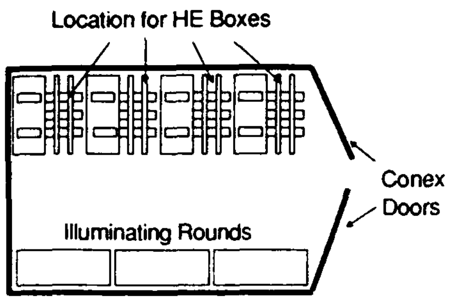
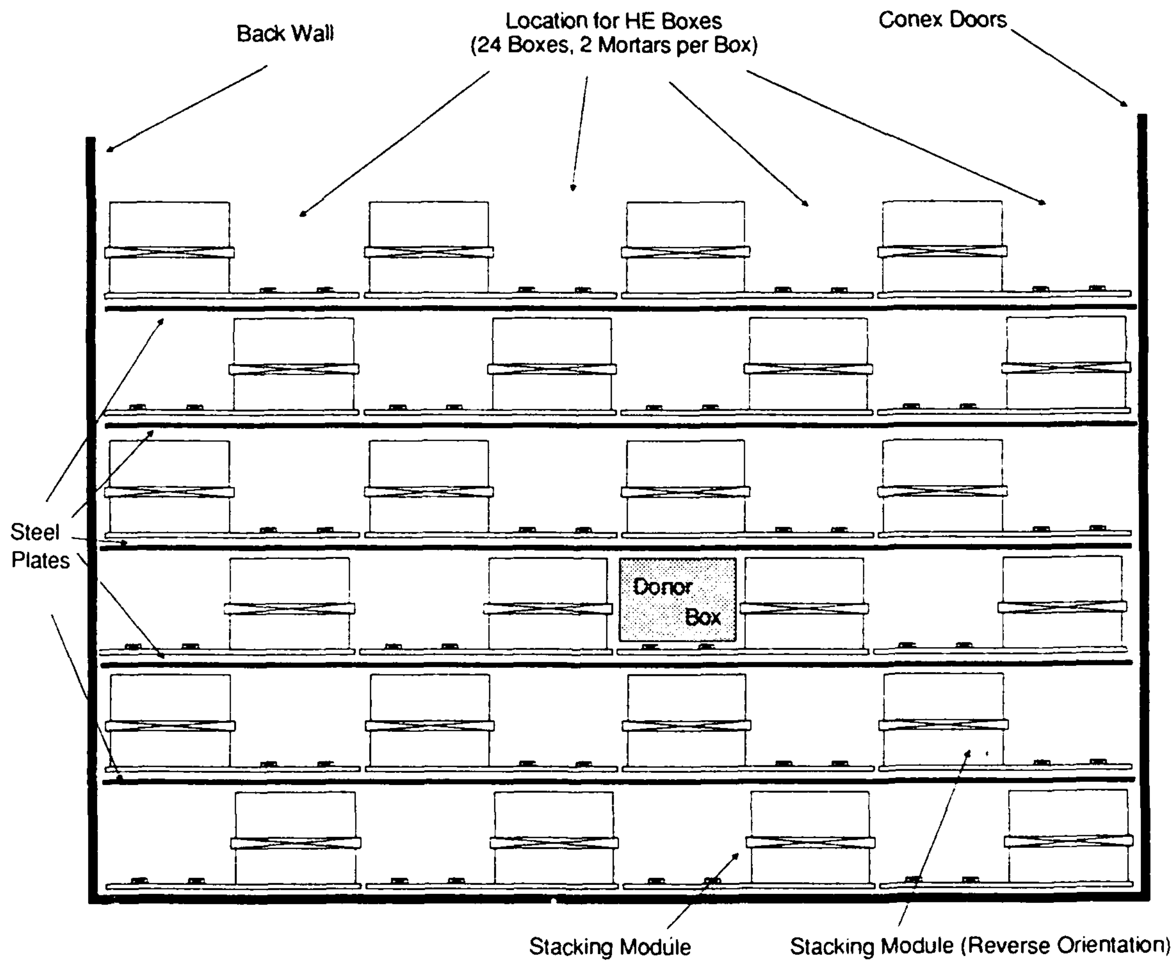


Figure 3. Assembled Rack (Without Mortar Boxes) for Test a Socorro, NM.

Assembled Rack (without mortar boxes)



Overhead View



Inside View of Rack

Figure 4. Assembled Rack (Without Mortar Boxes) for Tests at Utah Test and Training Range.

Wall Location

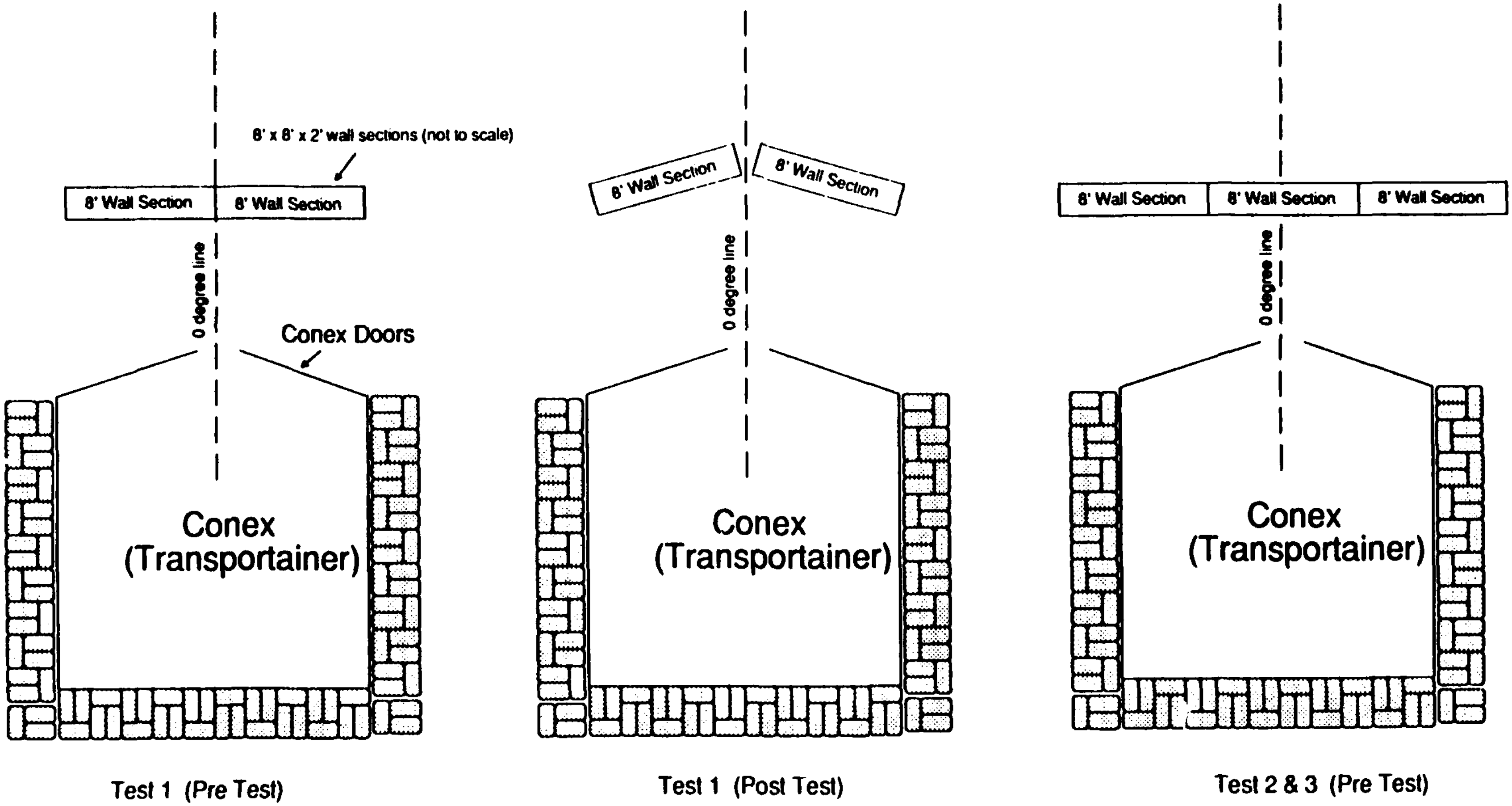
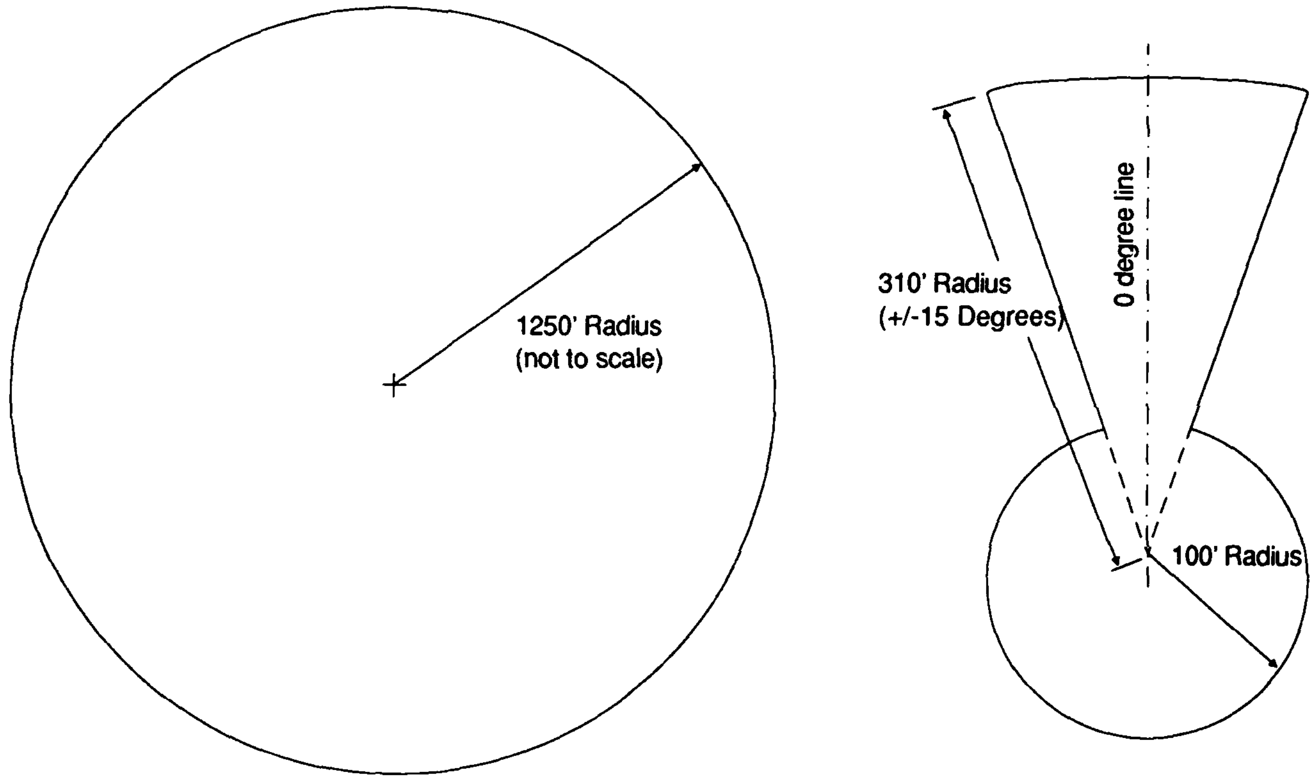


Figure 5. Location of Walls Used in Tests at Utah Test and Training Range.



Land Area required according to
DOD 6055.9 - STD = 4,908,738 sq. ft.
= 112.5 acres

Land Area required according to the
fragment dispersment = 53,957 sq. ft.
= 1.24 acres
= 1.1% of DOD 6055.9-STD's requirement

Figure 6. <u>Reduction in Danger Area Associated With Unprotected and Protected Storage</u>.

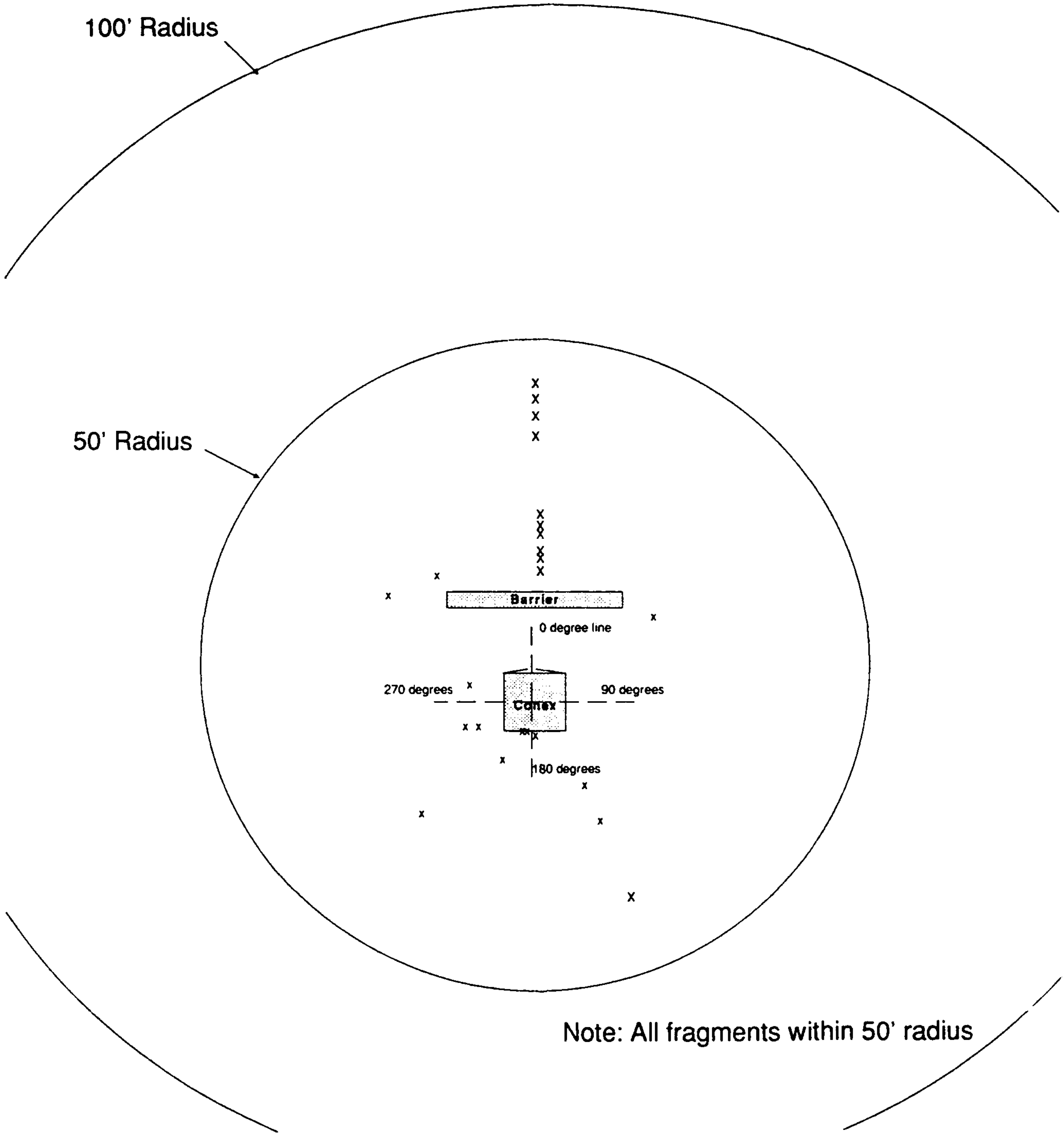


Figure 7. Plot of Fragment Locations From First Proof Test at Utah Test and Training Range.

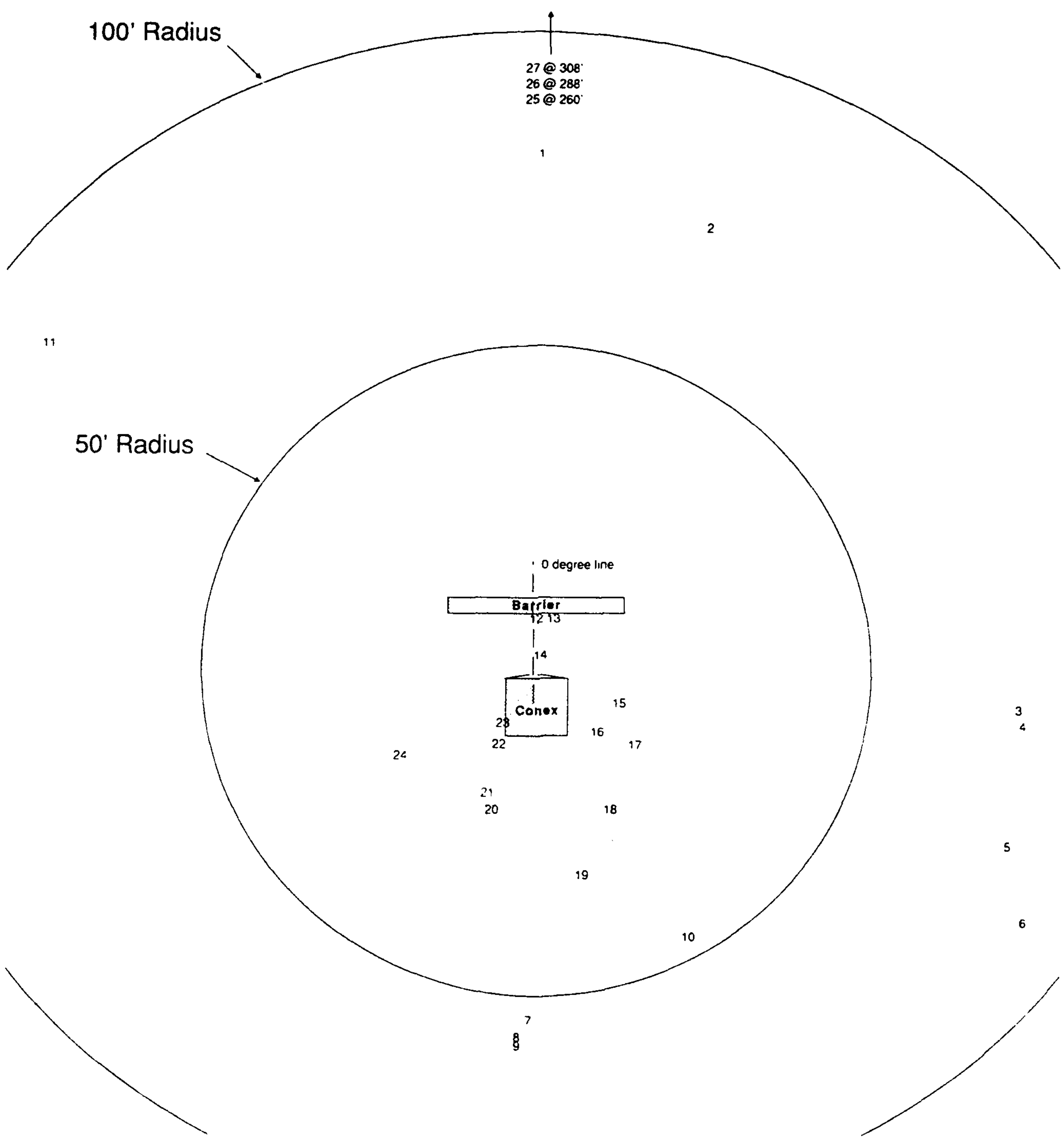


Figure 8. Plot of Fragment Locations From Second Proof Test at Utah Test and Training Range.

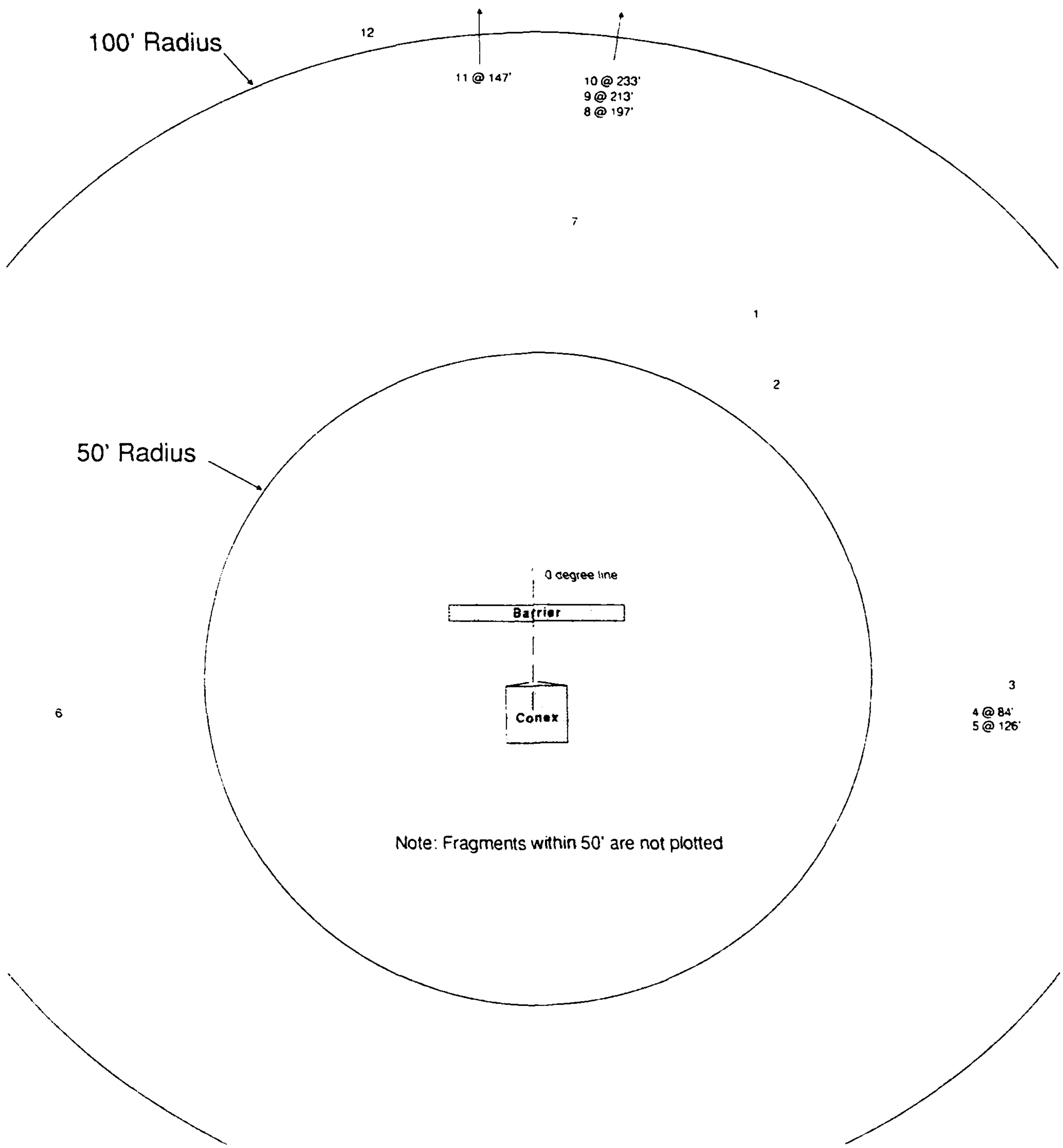


Figure 9. Plot of Fragment Locations From Third Proof Test at Utah Test and Training Range.

TWO-DIMENSIONAL SIMULATIONS OF SAND BARRIER MOTION INDUCED BY THE EXPLOSION OF AN AMMUNITION STACK INSIDE THE MAGAZINE

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Telephone: (410) 278-6210

ABSTRACT

Large quantities of explosives, frequently exceeding 100,000 lb, in different types of munitions may be stored in a single magazine. The storage of munitions has always presented safety problems, and various regulations have been developed over the years to ensure safe storage practices. In an effort to increase magazine limits, it has been proposed that the maximum credible event in an accident scenario may be significantly reduced if the munition store is divided into two or more stacks of ammunition separated by barriers designed to prevent propagation of an explosion from one stack to another. A combined analytical and experimental study was proposed to assess this hazard and to determine whether such barriers can be designed. The simulations were used to determine the velocity of a sand barrier on impact with an acceptor ammunition stack in order to design meaningful experiments. The donor ammunition stack was simulated by a volume of bare explosive. The initial position and size of the donor charge were varied in different computations. The thickness of the barrier was also varied. Velocity, pressure, and impulse histories were monitored at several stations in and near the barrier. Computational results show that the kinetic energy imparted to a barrier decreases with its thickness, indicating that thin fast-moving barriers have a potential to do greater damage to ammunition in an acceptor stack than thick slow-moving barriers. Thus, the barriers must be designed thick enough to prevent fragment penetration.

ACKNOWLEDGMENTS

This work was supported by the Project Manager for Ammunition Logistics, Picatinny Arsenal, NJ. Mr. O. Lyman of the U.S. Army Ballistic Research Laboratory, who was responsible for the experimental study, was instrumental in providing guidance on the magazine design and munitions stack arrangements which were used in this study.

1. INTRODUCTION

Large quantities of explosives, frequently exceeding 100,000 lb, in different types of munitions may be stored in a single magazine. The storage of ammunition has always presented safety problems, and various regulations have been developed over the years to ensure safe storage practices (DOD 6055.9 STD 1984; AR 385-64 1987). The situation is further complicated in areas where increased population density and reassessment of hazards have reduced the applicable explosive limits for existing magazines (Lyman 1983). To reduce the total land requirements for magazine facilities, it is desirable to limit the size of the maximum credible event to about 50,000 lb (further reductions don't reduce the safe inhabited building distance).

It has been suggested that the maximum credible event in an accident scenario may be significantly reduced if the munitions store is divided into two or more stacks of ammunition separated by barriers designed to prevent propagation of an explosion from one stack to another caused by fragments from the donor stack. For typical stacks of ammunition, this may require a wall of sandbags about 1 m thick. When using such a barrier to intercept fragments, the problem of the effect of its impact on the acceptor stack arises. While the fragment hazard may be eliminated, the moving barrier may cause sufficient damage to the munitions in the acceptor stack to initiate the explosive they contain, thus defeating its intended purpose.

A combined analytical and experimental investigation was proposed to assess this hazard and to determine whether such barriers can successfully be designed. The analytical study, which has been completed, included three numerical simulations using the HULL code. The first simulation was used to determine the velocity of the barrier on impact with the acceptor stack in the magazine environment in order to design meaningful experiments. In addition, several barrier design issues were addressed analytically. The second simulation was used to determine the experimental configuration required to produce the desired barrier velocity. The final simulation was used to assess the loading on typical acceptor ammunition that might be anticipated, in order to determine instrumentation requirements.

2. DESCRIPTION OF THE MAGAZINE AND AMMUNITION STACKS

Munitions must be stored such that they can be easily accessed, inspected, and inventoried. Dissimilar items are stored together, and each type must be available for removal without disturbing other stored munitions. Much of the munitions stockpile is stored in standard magazines. Elevation and plan views of such a structure including a proposed stack arrangement are shown in Figure 1.

The magazine is constructed with reinforced concrete walls, roof, and floor and is covered with earth. The interior of the magazine is semicylindrical, 24.38 m long and 8.00 m in diameter. A steel door, 1.22 m (4 ft) wide by 2.44 m (8 ft) high, is located in the middle of one of the end walls. The door is used for access in order to store or remove ammunition and also serves as a vent in case of an explosion inside the magazine.

Using palletized M107 155-mm projectiles, it is possible to store 506 pallets in a stack 3.35 m deep, reaching to the roof of the magazine. The high explosive weight per pallet is approximately 55.9 kg (123 lb), which gives 28,290 kg (62,238 lb) per stack. Up to four such stacks could be stored in a magazine, while still leaving room for barriers up to 1 m thick and 1 m of access space on each side of each stack.

3. DESCRIPTION OF THE PROPOSED EXPERIMENT

It is clearly impractical to conduct full-scale tests of candidate magazine configurations in order to find an arrangement which produces the desired results. As an alternative, tests in which a barrier segment is launched at a representative velocity toward an acceptor stack

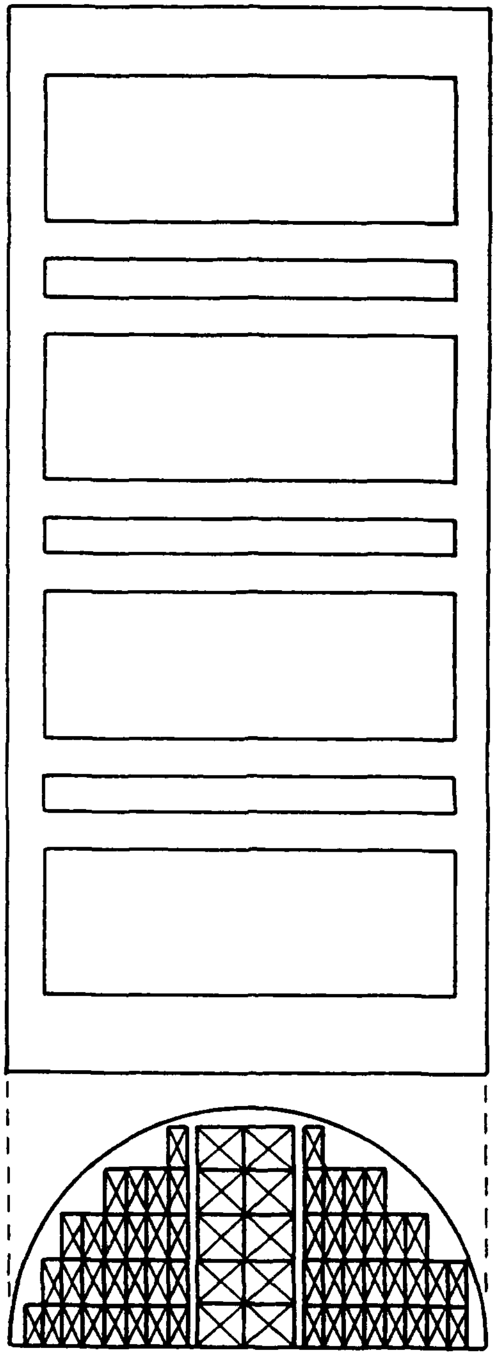

Figure 1. End Elevation and Plan Views of a Typical Magazine Showing a Proposed Stacking Arrangement.

segment have been proposed. In these tests, the barrier thickness remains full-scale, but its lateral extent is limited.

The test setup is illustrated schematically in Figure 2. In order to account for the lateral confinement provided by the full magazine environment, the tests are conducted in a trench 2 m deep, 3 m wide, and about 10 m long with a 2-m-thick earth overburden. The configuration is symmetrical, allowing two barriers to be launched toward two acceptor stacks by a central ammonium nitrate - fuel oil (ANFO) charge. The acceptor stacks include both live and inert 155-mm ammunition.

4. BRIEF DESCRIPTION OF THE HULL CODE

We used the HULL code to conduct the analytical study. The HULL system consists of programs for generating and solving two- and three-dimensional dynamic continuum mechanics problems in Eulerian and/or Lagrangian frameworks plus many peripheral programs required to provide graphical renditions of the results. Numerous constitutive models are included, and material parameters are provided in the HULL library. Detonation is treated by the programmed burn method. We used the two-dimensional Eulerian finite-difference capability (without heat conduction or viscosity) for our simulation and the graphics routines to obtain pressure and density contour plots as well as history plots (Hull User's Class).

5. DESCRIPTION OF THE MAGAZINE SIMULATION

In order to keep the size of the simulation manageable, we used a two-dimensional axisymmetric representation of the magazine as illustrated in Figure 3. The simulated magazine is thus a complete cylindrical shell structure having twice the interior volume of the actual semicylindrical magazine. Because of the absence of any angular motion component, a plane of symmetry exists at the magazine floor (or any similar plane), effectively providing a perfectly rigid surface.

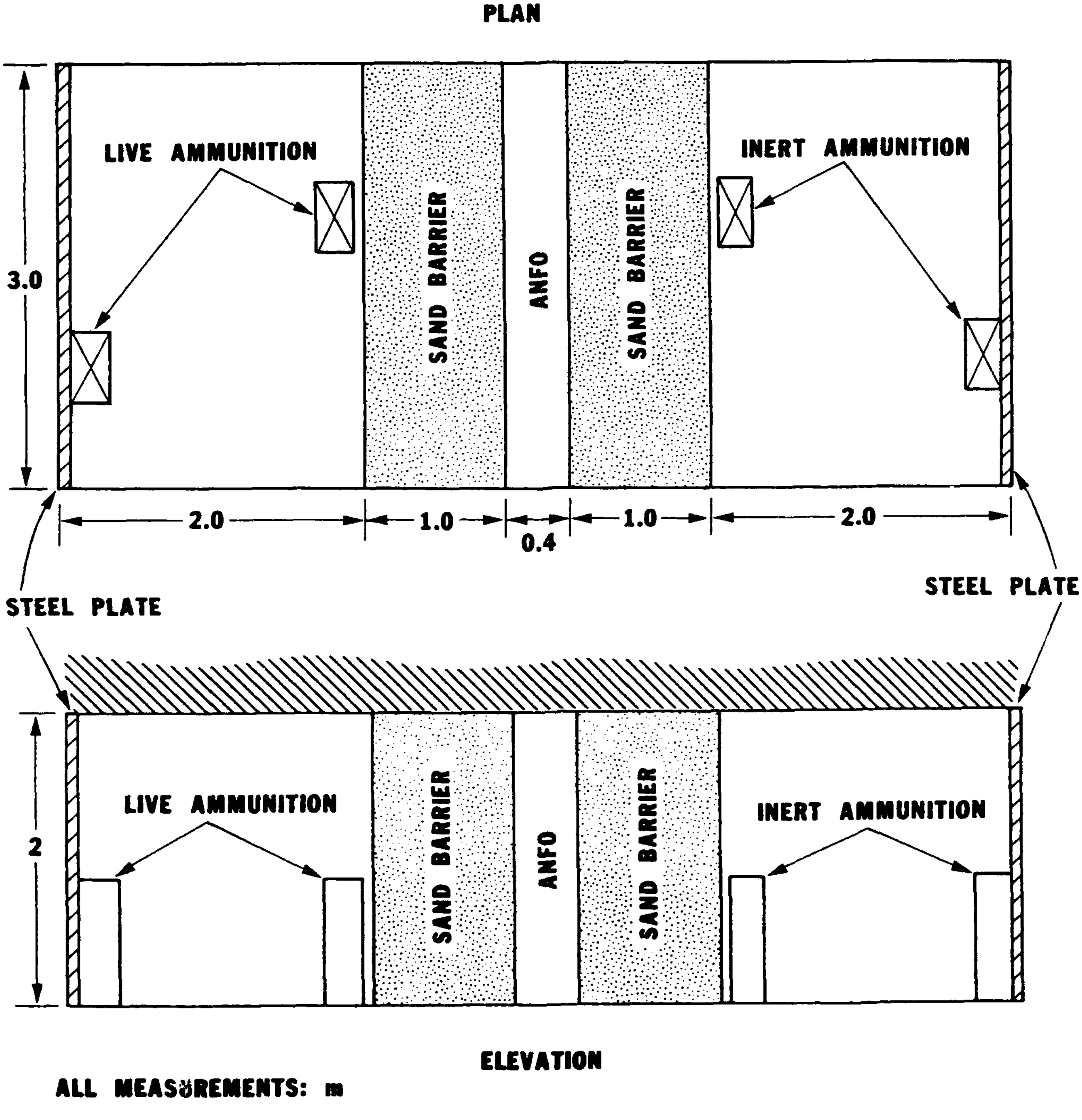

Figure 2. Side Elevation and Plan Views of the Proposed Experimental Arrangement.

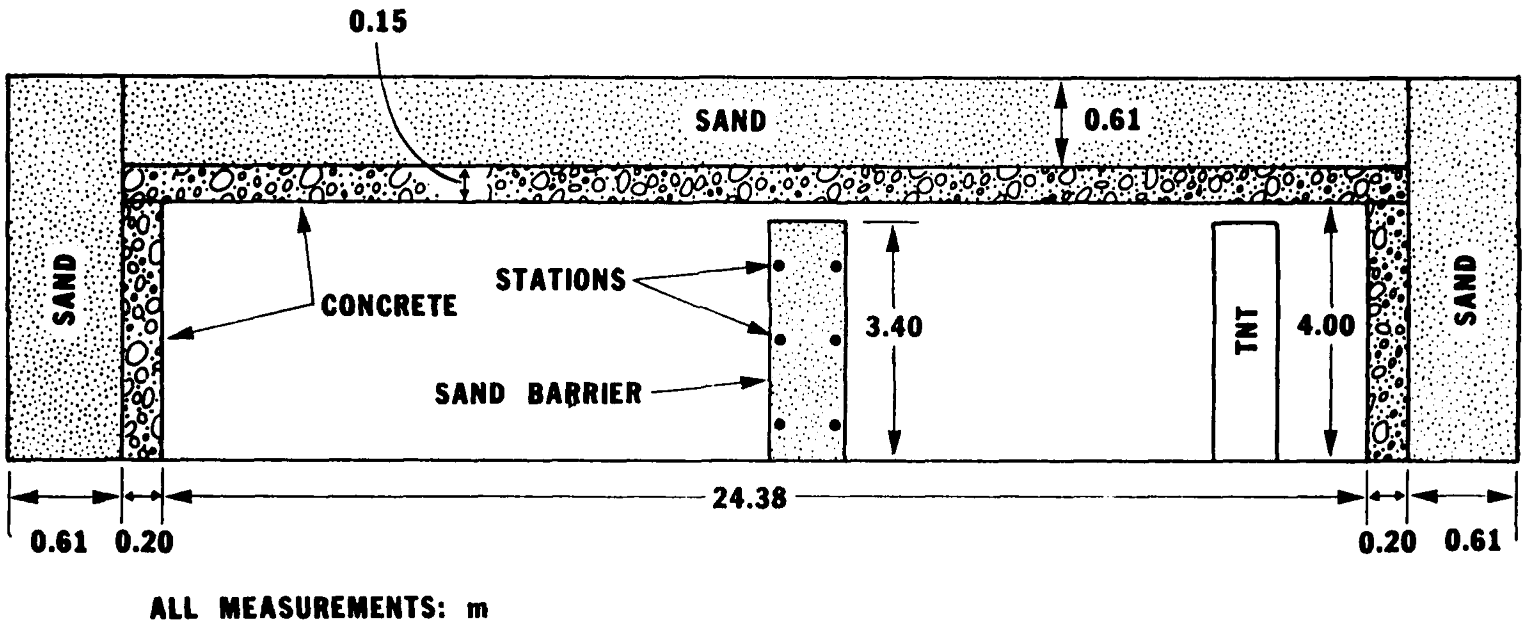

Figure 3. Magazine Configuration Simulation.

A concrete shell and end walls enclose the air-filled interior of the magazine, and a sand layer simulates the earth overburden. Air also fills the region surrounding the magazine. No attempt was made to represent the doors.

The donor ammunition stack is simulated by a cylinder of bare TNT representing (in the baseline case) 56.5 Mg (about 124,000 lb) or twice the actual mass (corresponding to the doubling of the interior volume). The initial position of the donor charge and its mass was varied in different computations. In each case, it was initiated on the axis at the center of the charge.

A sand barrier is placed near the center of the magazine. Sand wall thicknesses varying from 1 m to 3 m were modeled in different computations. In a few computations, vents (or open spaces) were left in the barriers to facilitate pressure equilibration across them. The vents were placed 1.0, 2.2, and 3.4 m above the floor. The size of the vents ranged from 0.20 to 0.60 m. Several stations in and near the sand barrier were chosen for monitoring velocity, pressure, and impulse histories. These are shown in Figure 4.

The computational region was discretized into 350 zones covering 28 m in the axial direction and 75 zones covering 6 m in the radial direction.

Equations of state for air, concrete, sand, and TNT products (Jones-Wilkins-Lee [JWL]) were taken from the materials library of the HULL code.

6. RESULTS OF THE MAGAZINE SIMULATION

Figures 5a through 5e shows a series of pressure and density contour plots for a typical computation. Pressure contours are shown on the left side of the axis and density on the right. After the TNT detonated, it took about 3 to 4 ms for the blast wave to arrive at the sand barrier. Acceleration of the wall took place over a considerably longer period of time. Each computation was allowed to run for 30 to 40 ms. This was more than enough time to produce a steady wall velocity. The contour plots show increasing diffusion of the material boundaries

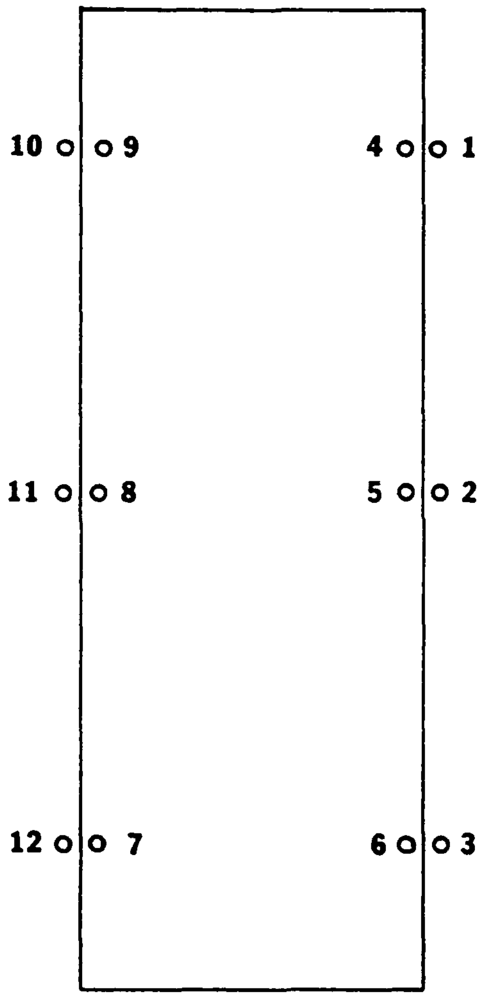

Figure 4. Locations of the Lagrangian Stations In and Near the Barrier.

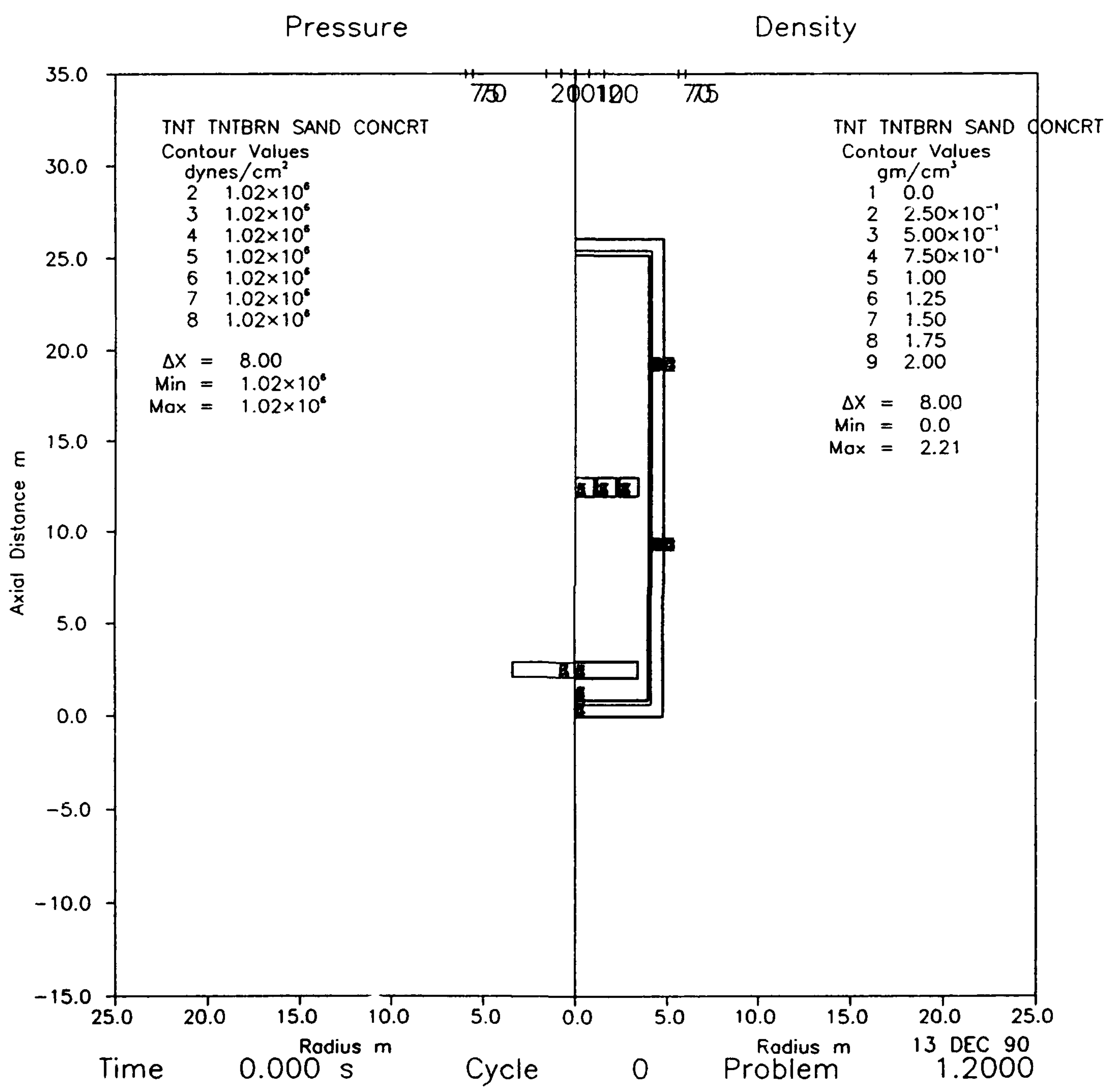

Figure 5a. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 0 ms.

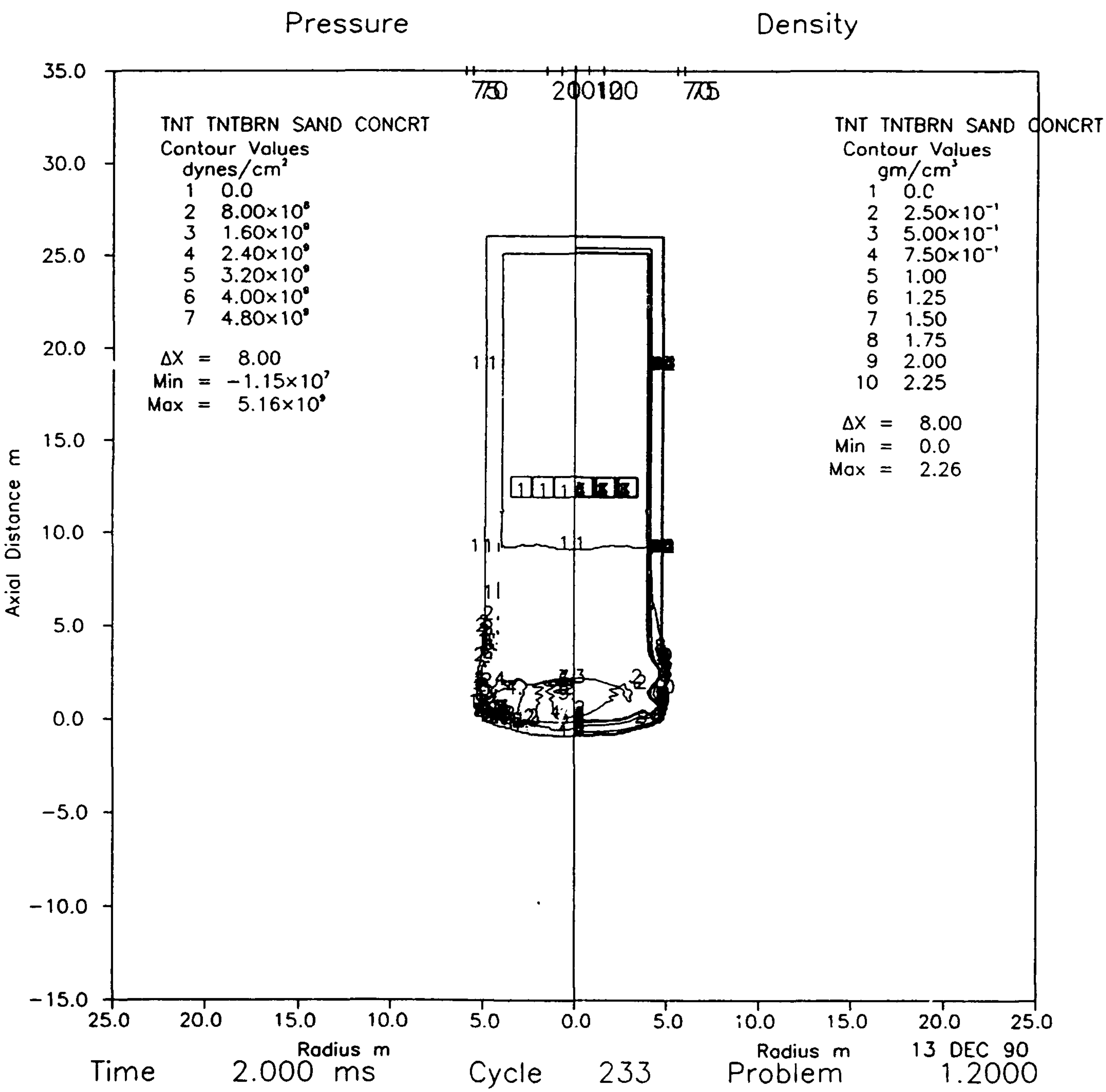

Figure 5b. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 2 ms.

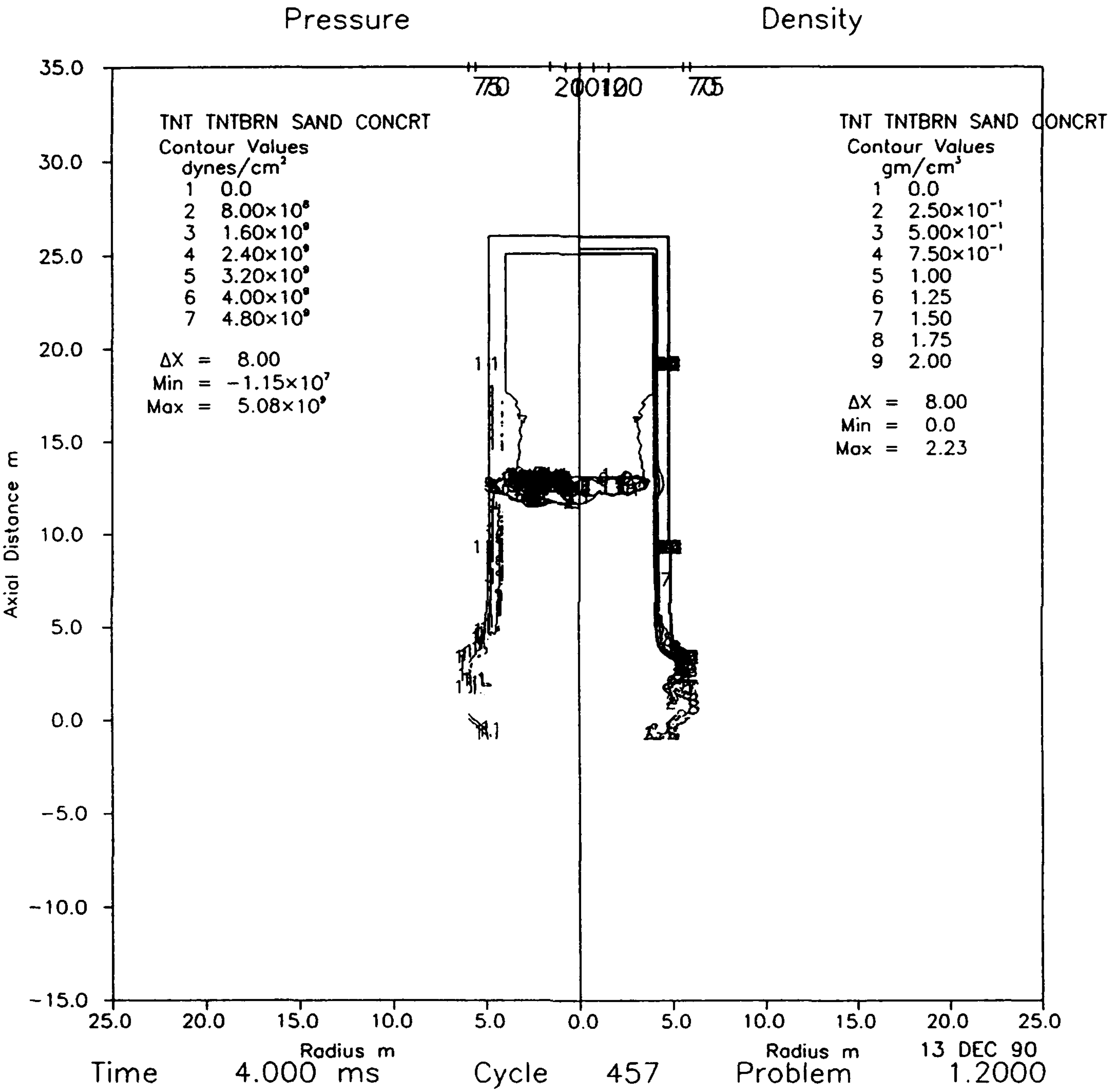

Figure 5c. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 4 ms.

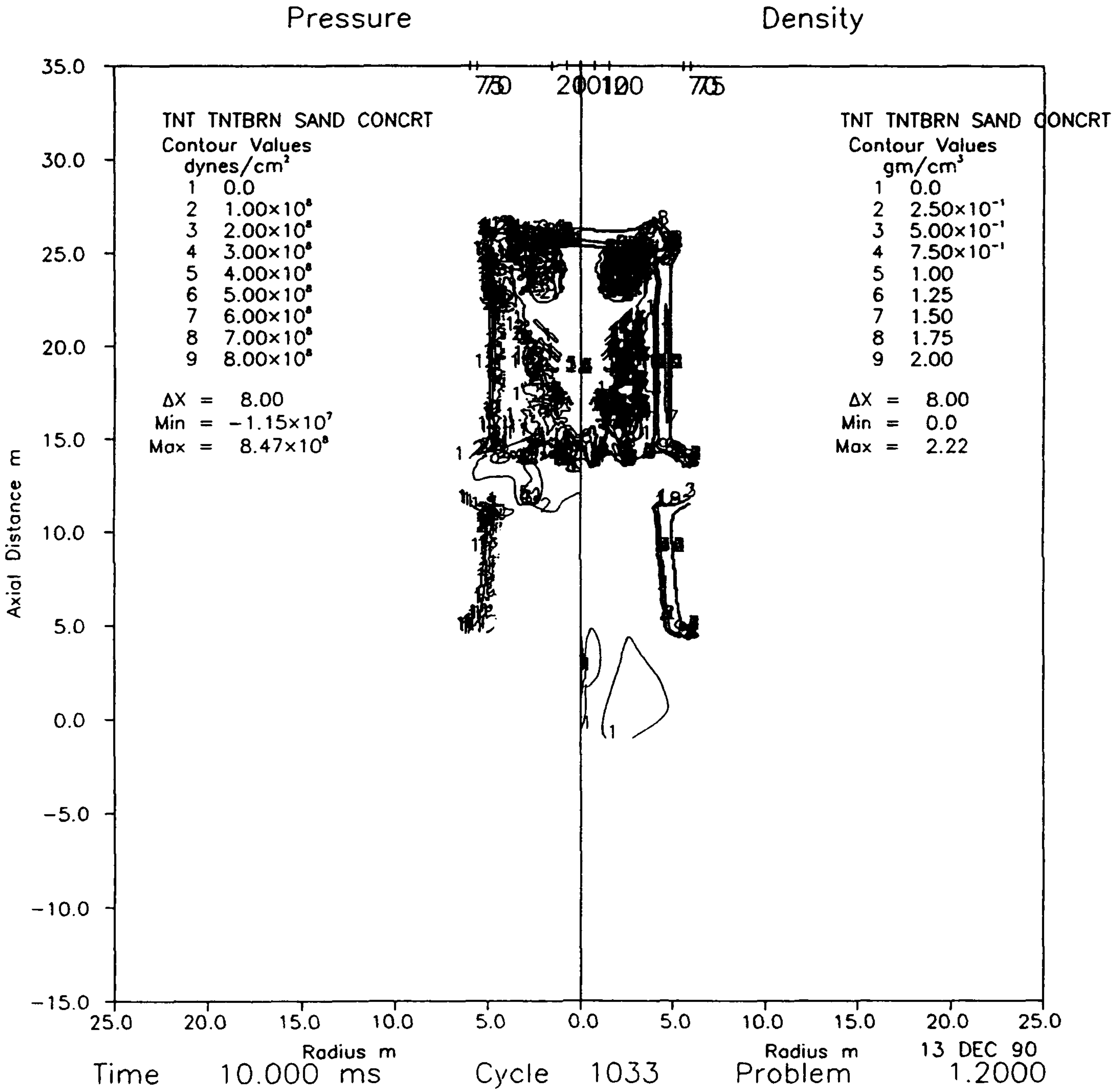

Figure 5d. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 10.0 ms.

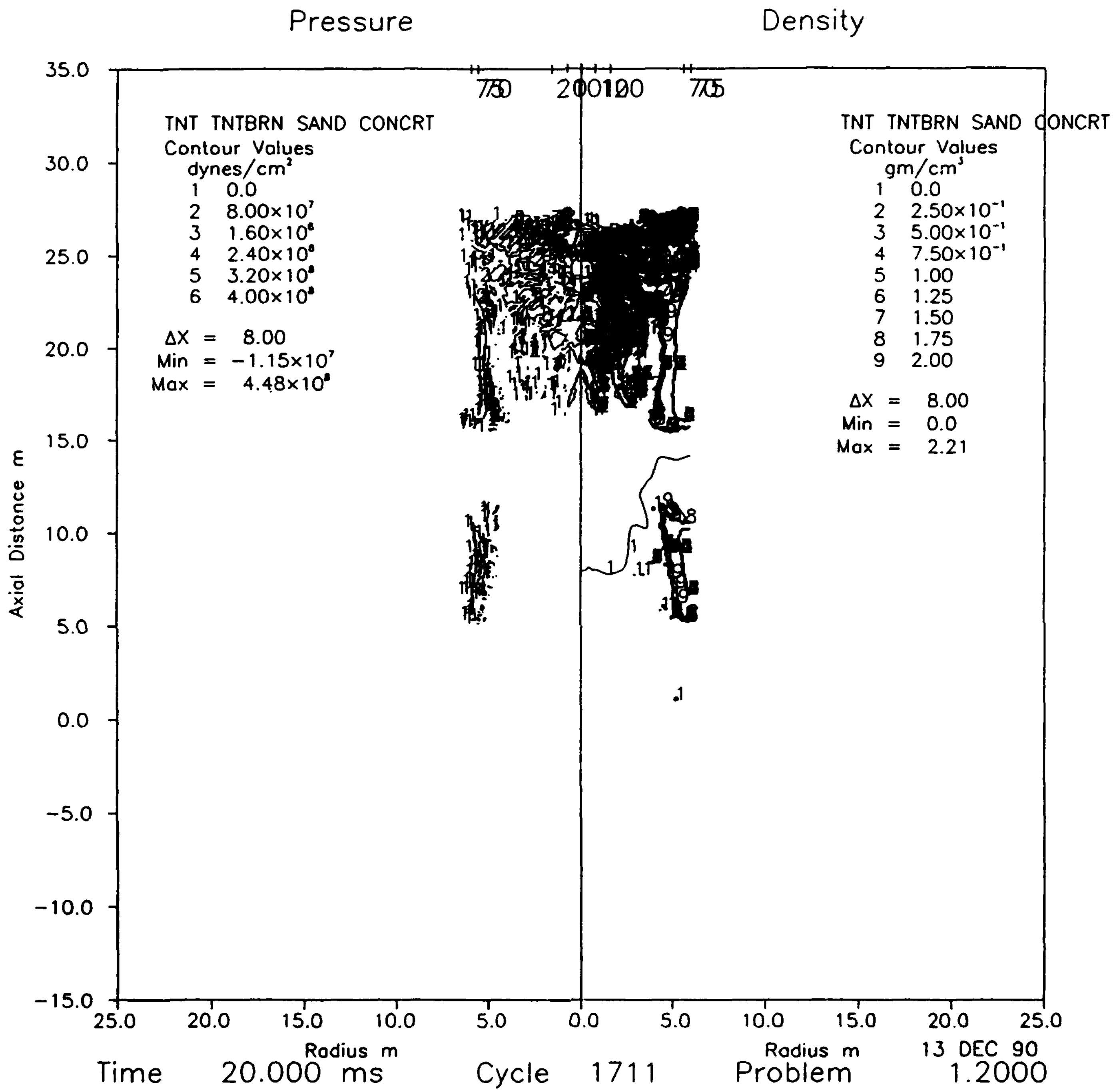

Figure 5e. Pressure and Density Contour Plots for a Representative Magazine Simulation Computation, 20.0 ms.

at late time. Corresponding plots of velocity history at several of the stations are shown in Figure 6. Somewhat different steady-state values are produced at the different stations. A total of 18 computations were completed. The steady-state velocities computed at stations 7, 8, and 9 (near the leading edge of the barrier) are summarized in Table 1 along with the average velocity at all the stations in the barrier. Some variation in the velocity from station to station is evident, but the general trends remain clear.

As the barrier thickness is increased while retaining a separation of 5.0 m between the center of the charge and the center of the barrier with a 28.2-Mg charge, the resulting terminal velocity decreases. Average terminal velocity is plotted as a function of barrier thickness in Figure 7a. As the separation distance is increased, the terminal velocity decreases as shown in Figure 7b. Approximate representations of the barrier momentum and kinetic energy per unit area may be obtained by multiplying the initial barrier mass per unit area by the velocity and half the square of the velocity, respectively. These are plotted as functions of barrier thickness in Figure 8. The results are most consistent with constant momentum and show decreasing kinetic energy with increasing thickness.

Venting of the barriers left their terminal velocities virtually unchanged as is evident in Table 1.

The distances between the barrier and the donor charge and the mass of the donor charge were also varied in different computations. Blast scaling laws suggest that the impulse delivered, and, hence, the terminal momentum of the barrier, is a function of the scale distance defined by dividing the physical distance by the cube root of the charge mass. The variations in approximate terminal momentum as a function of scale distance are shown in Figure 9. The results indicate that this relationship is reasonably well followed especially at larger scale distances.

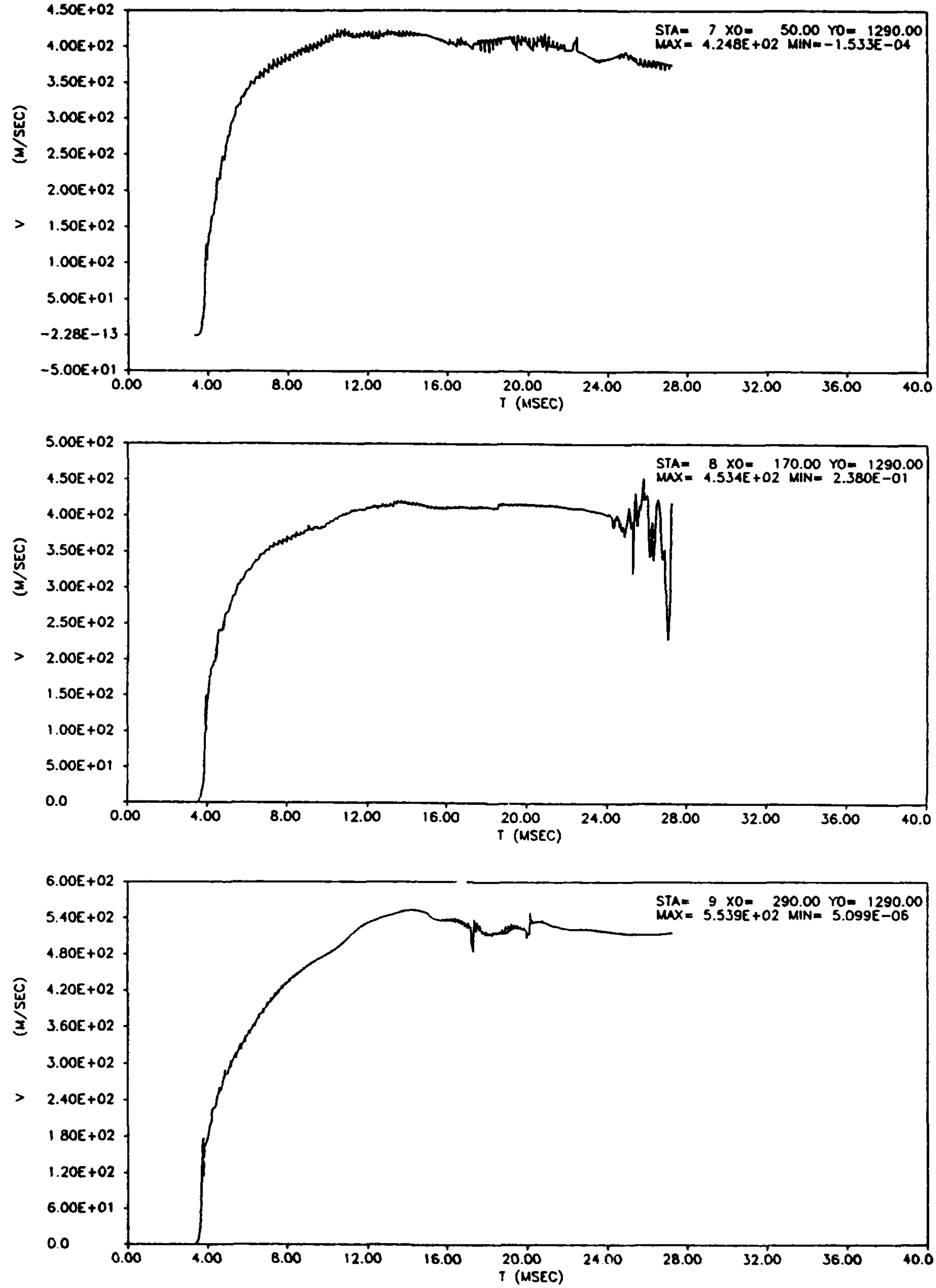

Figure 6. Velocity Histories at Several Lagrangian Stations for a Representative Magazine Simulation Computation.

Table 1. Summary of Magazine Computations

Charge Mass (Mg)	Barrier Thickness (m)	Center-to-Center Separation (m)	Terminal Velocity at Station 7 (m/s)	8 (m/s)	9 (m/s)	Average Terminal Velocity (m/s)
19.5	2.0	5.0	200	200	170	208
28.2	0.5	5.0	900	900	800	867
28.2	1.0	5.0	500	560	460	514
28.2	1.0	10.0	440	385	510	437
28.2	1.0[a]	10.0	420	400	500	443
28.2	1.0	11.0	450	400	530	415
28.2	2.0	5.0	320	290	255	290
28.2	2.0	5.5	300	280	235	282
28.2	2.0	7.5	225	230	190	224
28.2	2.0	10.5	240	240	230	210
28.2	2.0[a]	10.5	220	240	210	206
28.2	3.0	5.0	200	200	160	195
28.2	3.0	6.0	180	180	140	172
28.2	3.0	8.0	150	150	100	158
28.2	3.0	11.0	120	140	115	142
28.2	3.0[a]	11.0	120	120	140	128
32.4	2.0	5.0	360	360	320	328
37.0	2.0	5.0	400	400	400	380

[a]vented barrier

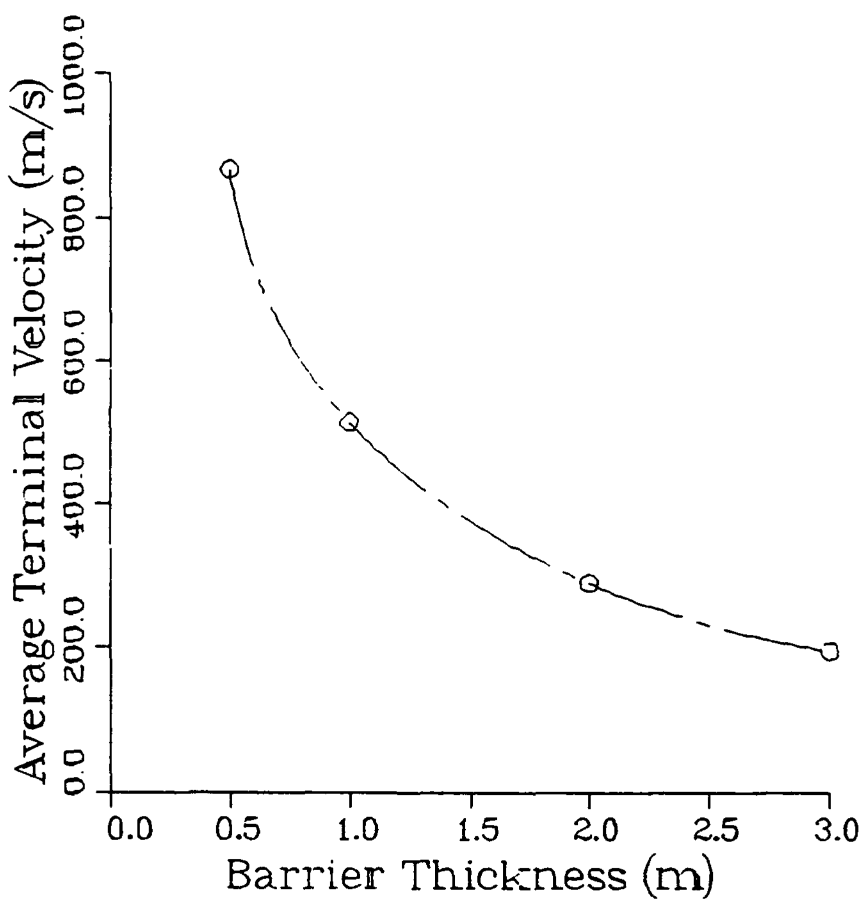

Figure 7a. Average Terminal Velocity as a Function of Barrier Thickness for a Charge Center to Barrier Center Separation Distance of 5.0 m.

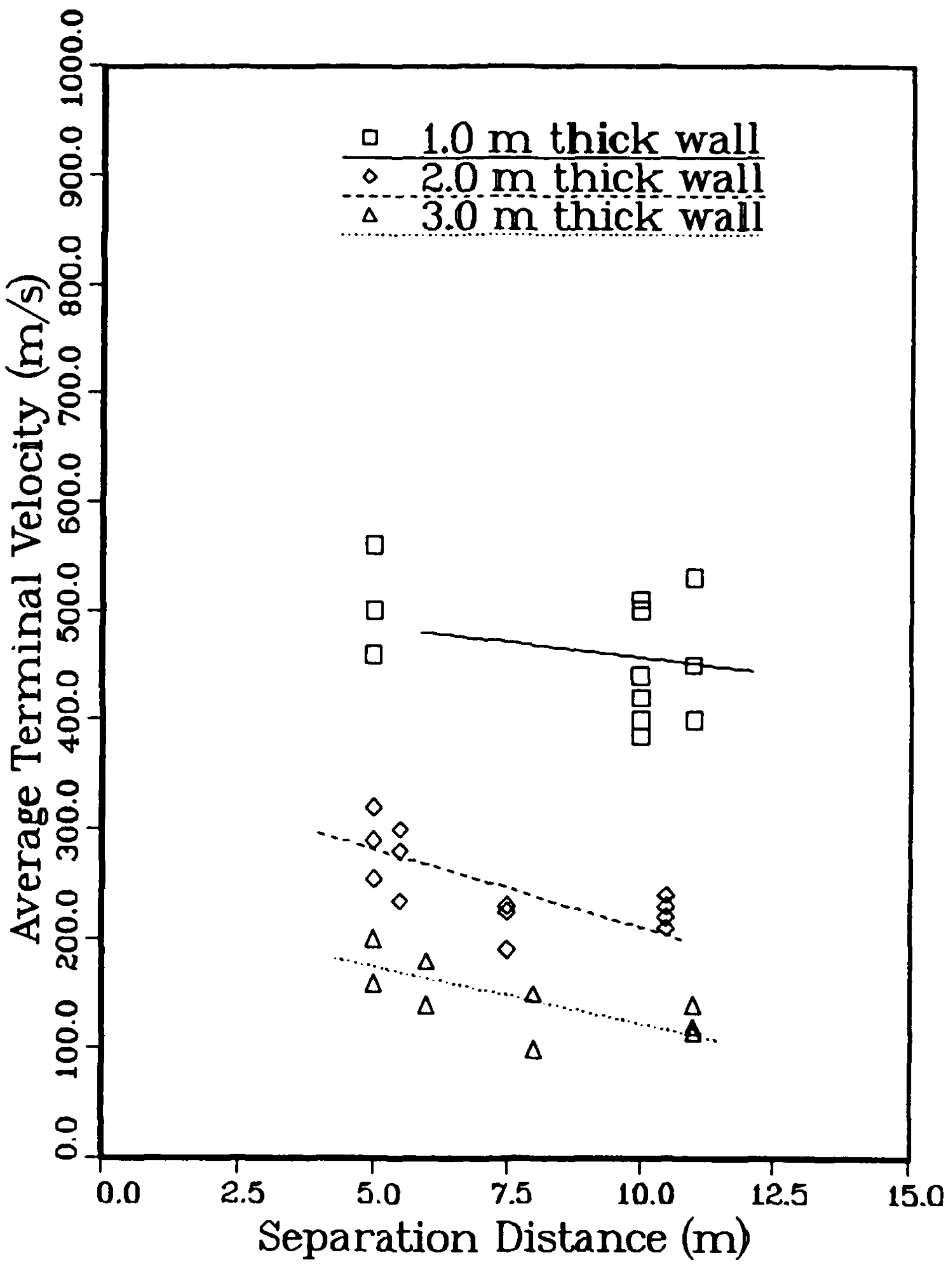

Figure 7b. Average Terminal Velocity as a Function of Separation Distance.

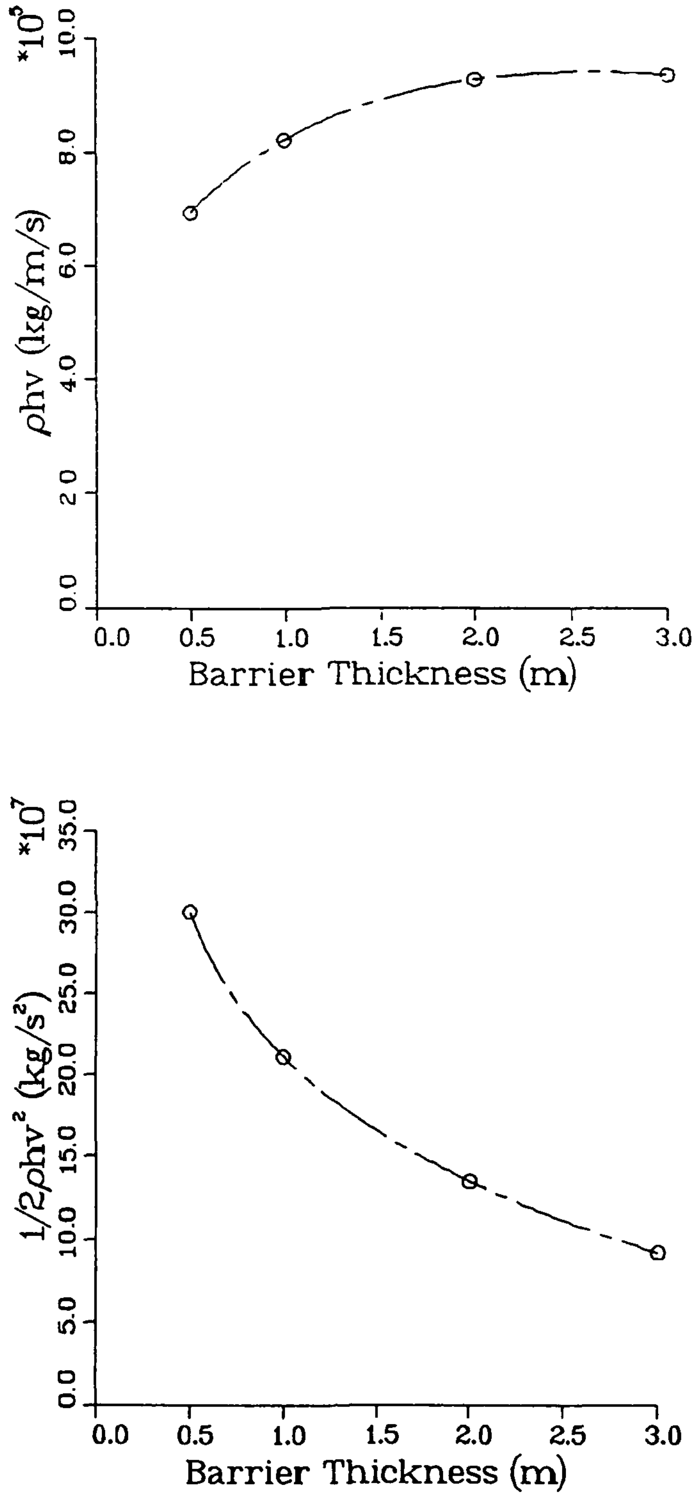

Figure 8. Approximate Terminal Momentum and Kinetic Energy as Functions of Barrier Thickness for a Charge Center to Barrier Center Separation Distance of 5.0 m.

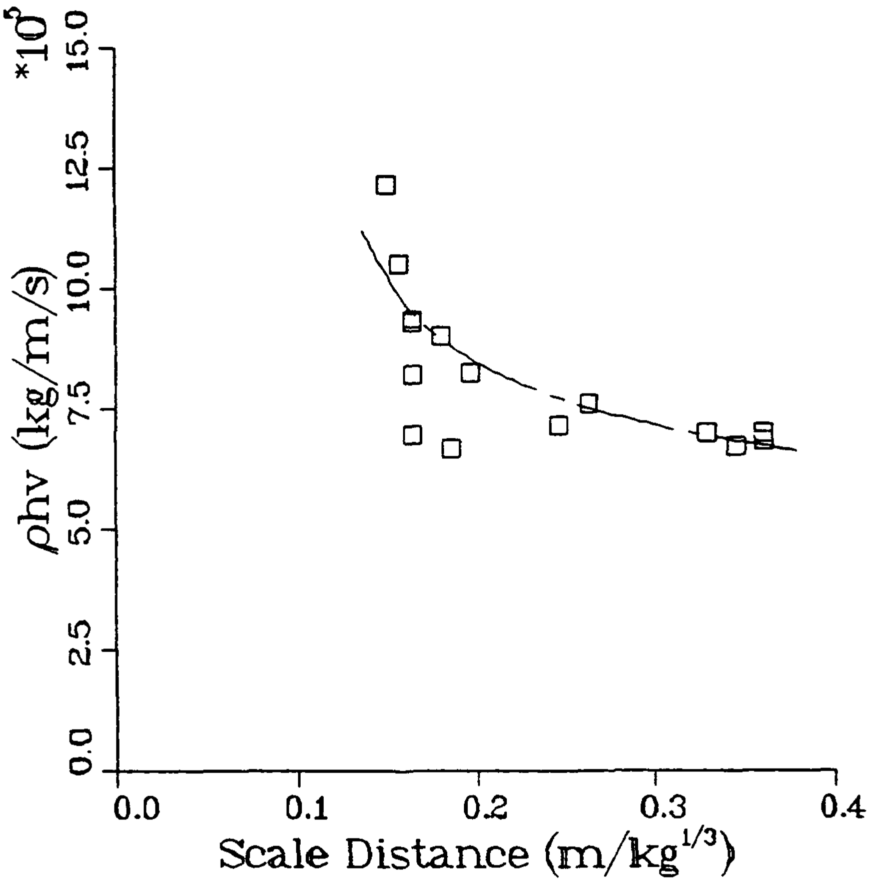

Figure 9. Approximate Terminal Momentum as a Function of Scale for All Computation.

7. DESCRIPTION AND RESULTS OF THE TEST SIMULATION

A simulation of the experimental configuration, as illustrated in Figure 10, was also made. Axisymmetry was deemed the best way to represent the lateral confinement in a two-dimensional simulation. Additional symmetry is afforded by the experimental setup in which identical sand-filled barriers are arranged on either side of a TNT or ANFO charge which fills the space between them. The computational region thus extends from the center of the charge (where a reflective plane is placed) to a point 2 m beyond the end of the trench. The thickness of the barrier was maintained at 1 m in all the computations, but the thickness of the charge was varied from 0.30 to 0.40 m in different computations. The velocity of the wall was monitored at three locations (r=0.50, 1.00, and 1.50 m) along the radial axis, as shown in Figure 10.

Representative velocity histories are shown in Figure 11. Because the driving explosive is initially in contact with the barrier, the barrier does not quite reach terminal velocity before striking the end of the trench. The maximum velocities determined in four computations are summarized in Table 2.

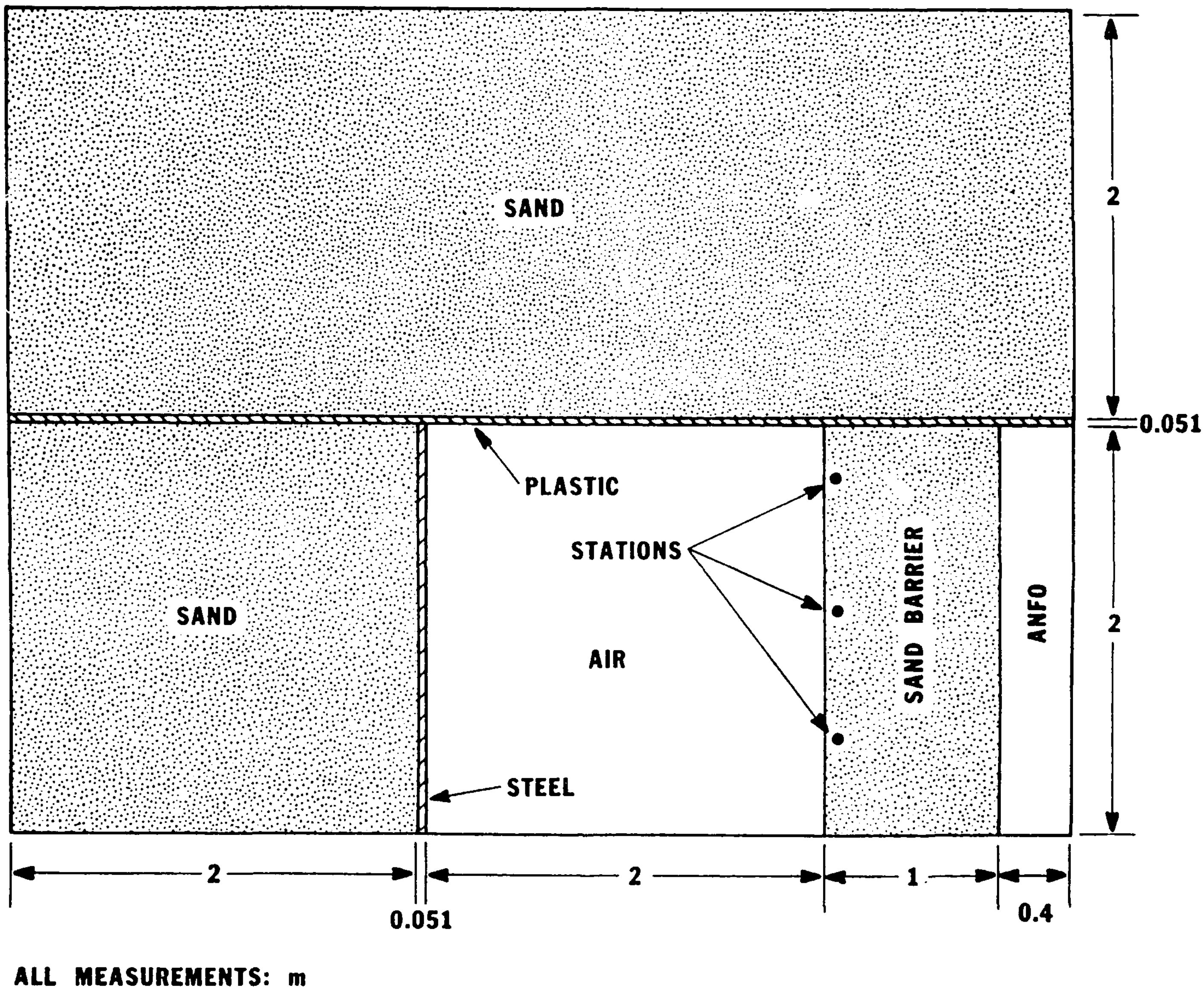

Figure 10. Experiment Simulation Configuration Showing the Locations of the Lagrangian Stations.

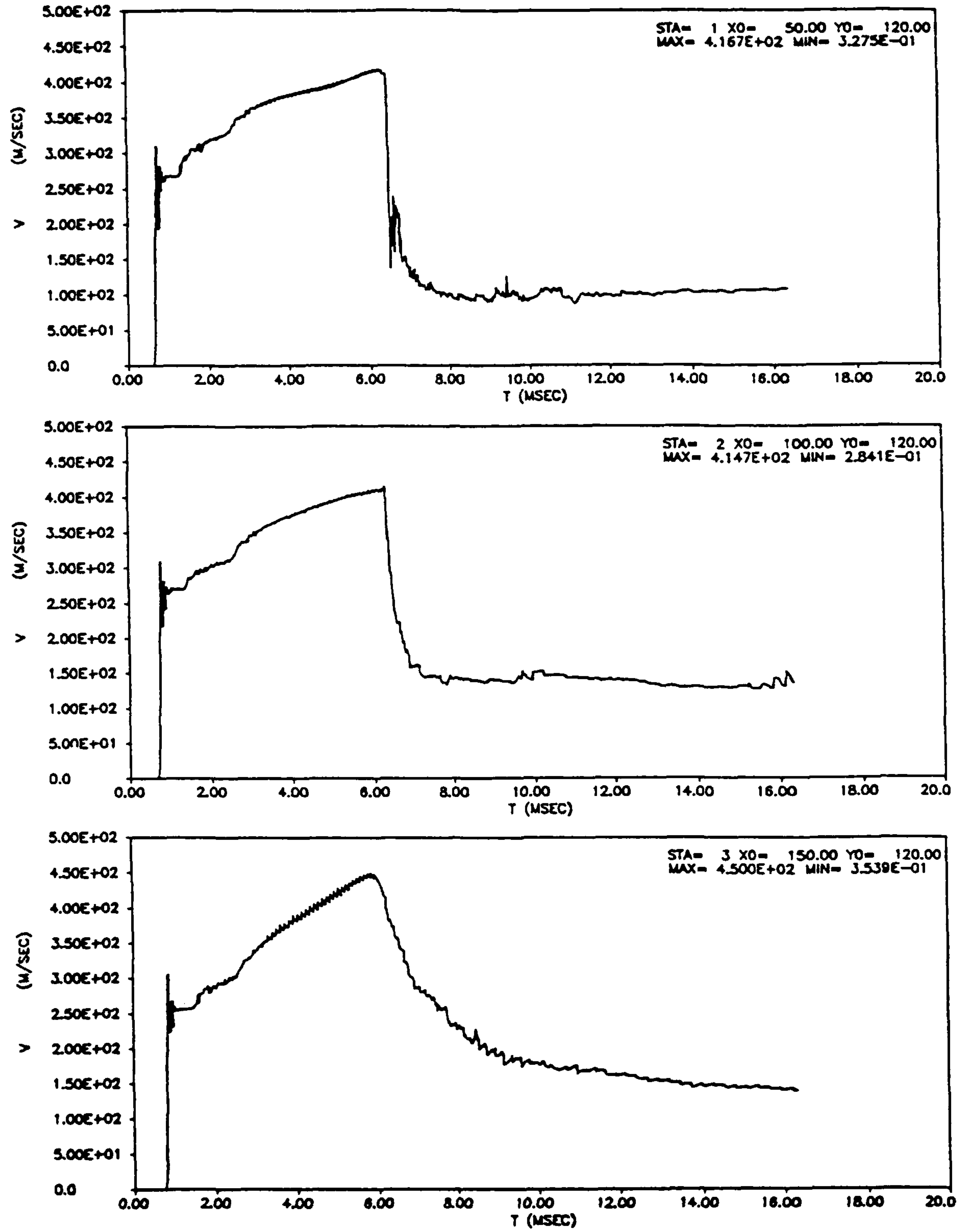

Figure 11. Velocity Histories at Several Lagrangian Stations for a Representative Test Simulation Computation.

Table 2. Summary of Test Simulation Computations

Charge Explosive	Thickness (m)	Maximum Velocity at Station 1 (m/s)	2 (m/s)	3 (m/s)	Average Velocity (m/s)
TNT	0.20	270	280	320	290
TNT	0.30	450	450	480	460
ANFO	0.30	320	320	350	330
ANFO	0.40	400	400	450	417

8. DESCRIPTION AND RESULTS OF THE ACCEPTOR RESPONSE SIMULATION

A final calculation was made to determine the pressure that might be expected inside a 155-mm M107 artillery round subjected to barrier impact at 360 m/s. The problem configuration including the locations of the pressure monitoring stations is shown in Figure 12. The computed pressure histories are shown in Figure 13. The pressures observed were generally lower than 0.35 GPa.

9. SUMMARY AND CONCLUSIONS

The fact that the kinetic energy imparted to a barrier decreases with its thickness indicates that thin fast-moving barriers have the potential to do greater damage to ammunition in an acceptor stack than thick slow-moving barriers. Barriers must be designed thick enough to prevent fragment penetration. Additional thickness, where possible, is also desirable.

The terminal momentum of the barriers was found to be roughly constant for a given charge mass and location. The application of blast scaling laws showed that these might be useful as predictive tools when the distance between stack and barrier is not too small.

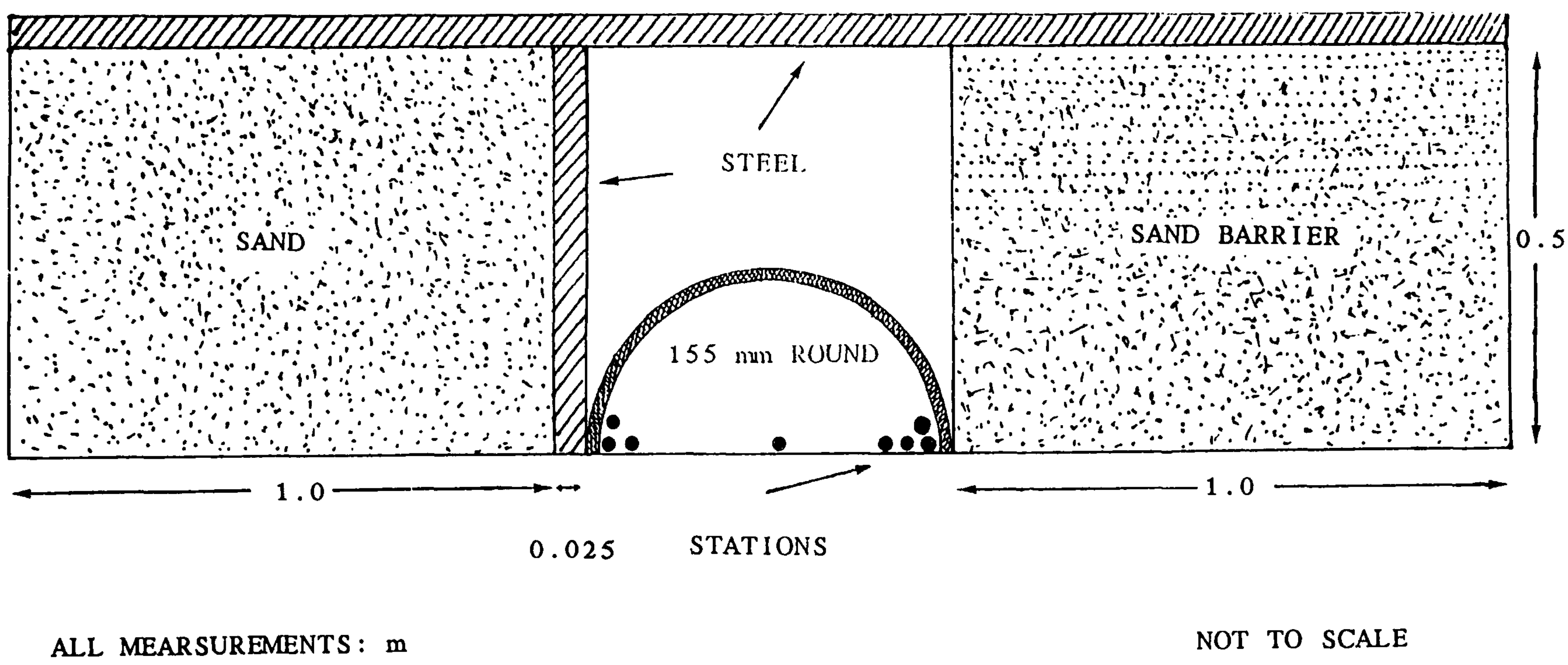

Figure 12. Munition Response Simulation Configuration Showing the Locations of the Lagrangian Stations.

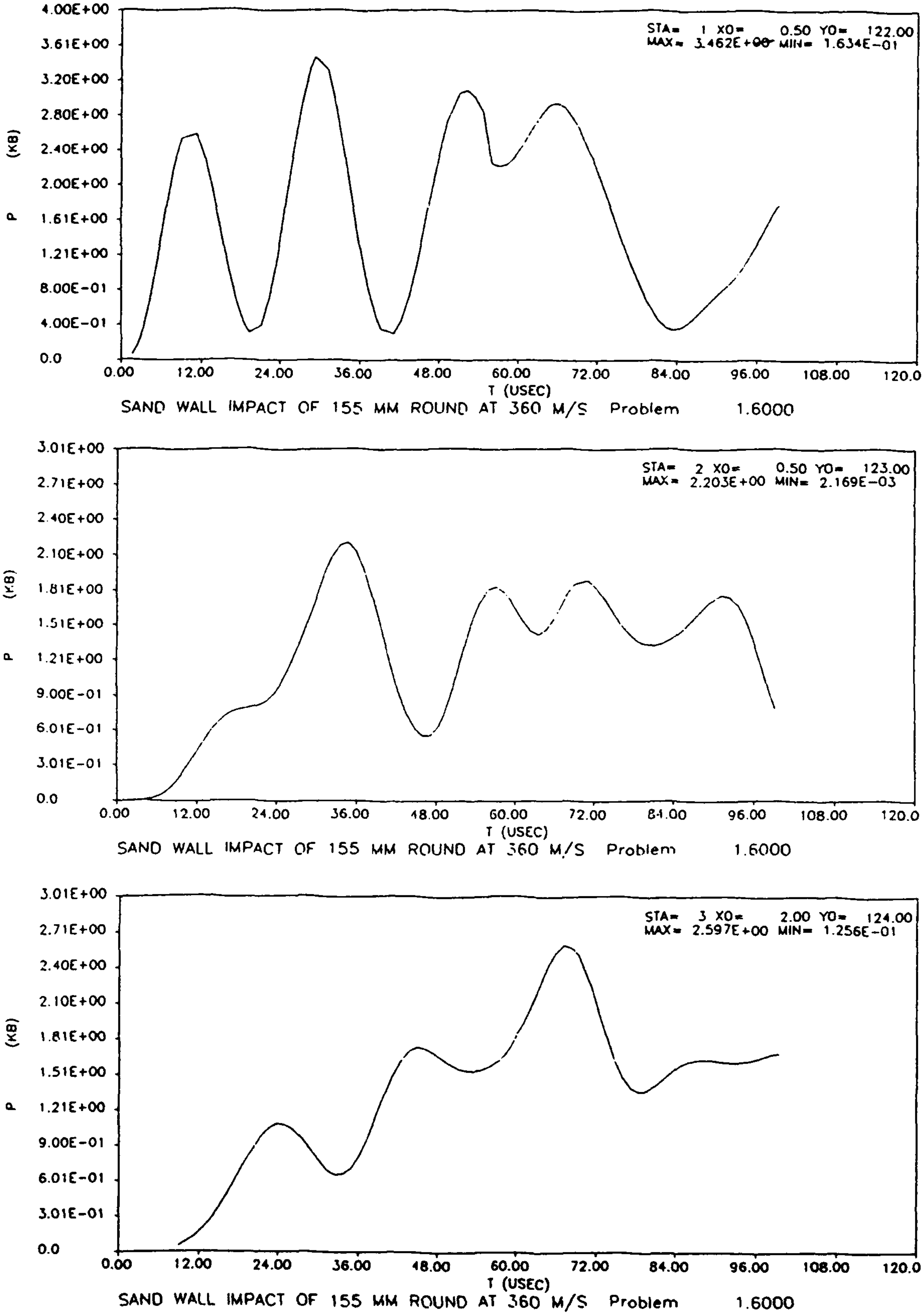

Figure 13. Pressure Histories at the Lagrangian Stations for the Munition Response Simulation.

Terminal velocities were not significantly reduced when vents were placed in the barriers. Thus, these computations provide little support for this technique as a method for mitigating the hazard posed by moving barriers.

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THE MECHANISMS AND PARAMETERS OF ABRASIVE WATERJET (AWJ) CUTTING OF HIGH-EXPLOSIVE PROJECTILES

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Principal Researcher

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ABSTRACT

Alliant Techsystems has researched sectioning high-explosive projectiles with abrasive waterjets (AWJ) and has examined the physical mechanisms of the process. In addition to performing parametric studies of waterjets, Alliant Techsystems has cut over 170,000 high-explosive projectiles under controlled conditions to evaluate the safety of the waterjet cutting process. Here, the various parameters that affect the safety and performance of the abrasive waterjet cutting process are described and the relative merits of the different options are compared. Specifically, the safety-critical parameters are the diameter of the jet stream and the velocity of the water. With these safety critical parameters, the likelihood of an initiation can be predicted for a given explosive using existing projectile impact models developed by various laboratories.

August 1992

INTRODUCTION

Background

Once the Defense Systems Group of Honeywell, Alliant Techsystems is now a fully independent company and takes its place as one of the largest designers and producers of conventional ammunition in the world. As part of our continuing effort for technical excellence, we have pursued a number of new technologies, including this field of waterjet cutting of explosives. The investigation of waterjets as an unconventional machining technology was in response to an internal need to safely cut high-explosive projectiles.

As supported by other papers presented by Alliant Techsystems at this Department of Defense Explosive Safety Board Seminar, we have established that waterjets are a safe method for working with high explosives. After a thorough tradeoff study, the use of waterjets was sanctioned within our company as fully meeting our needs for a safe and efficient method of cutting high-explosive ammunition prior to either explosive recovery or incineration. This research into the performance parameters and limits of safe operation has taken us almost two years to complete.

Our research was separated into both a theoretical portion and an empirical testing program. The testing operations were further split into seven specific phases, four of which will be discussed in this paper. Deliberate care was taken at each step to structure the test sequences in such a way as to ensure that the information gathered was statistically accurate. Although not exhaustive, this paper describes the mechanisms and parameters we found useful for operating waterjets, including the results of our safety test sequence of abrasive waterjet cutting approximately 170,000 high-explosive projectiles.

Definitions

Some definition of terms must first be made in order to prevent confusion with existing products that also have been used on explosives:

Waterjet (WJ) — A process utilizing high-pressure water, up to 410 MPa (60 ksi), forced through an orifice (Figure 1). The particle velocity of waterjets is usually very high, up to a maximum of 0.9 km/s, and is capable of directly cutting many low-yield-strength materials without the use of additional abrasives. In the United States, the major producers are Flow, Ingersoll-Rand, and Jet-Edge.

Abrasive Waterjet (AWJ) — A waterjet that, after the water passes through the orifice, entrains abrasive particles by aspiration and mixes them by mechanical action into the high-velocity stream of water inside a focusing tube (Figure 2). Depending on the abrasive and other parameters, abrasive waterjets can cut through virtually any material.

Abrasive Slurryjet (ASJ) — A system that utilizes mixed water and abrasive slurry, which is then pressurized and the slurry mixture forced through a nozzle (Figure 3). Although abrasive slurryjets are potentially more efficient than abrasive waterjets when operated at the same pressure, the current production equipment pressure levels are only about 20 percent that of abrasive waterjets and have a proportionally lower efficiency.

Cavitating Waterjet (CWJ) — An intermediate pressure, approximately 68 MPa (10 ksi), water stream process with a special nozzle that induces "natural cavitation" (vapor bubble formation) in

the water flow (Figure 4). The cavitating waterjet process involves the initiation, growth, and impact of vapor bubbles against the target material. The collapse of these vapor bubbles causes intense, localized impacts in a highly variable manner to erode the target material. It is important to note that cavitating waterjets are *not* the same thing as waterjets in the waterjet industry. Although cavitating waterjets have historically been used on explosives,[1] they are not related to the safety tests described in this paper and no extrapolation of results should be made simply because they have similar names.

Operational Description

The operation of a waterjet can be simplistically stated as a pump (Figure 5) that pressurizes water up to 410 MPa (60 ksi) and delivers the water through a small orifice, ranging in size from 0.13 mm (0.005 in.) to 1.32 mm (0.052 in.) in diameter, as a continuous stream. This continuous stream of water is traveling at velocities approaching 825 m/s (3000 f/s) and impacts the target material, causing erosion at a rate dependent on the mass and velocity of the water and the yield strength of the target material. As shown in Figure 1, the number of components used in a waterjet are few and appear deceptively simple. What is difficult to show in this diagram is the stress on the equipment and the precision machining necessary for the system to remain reliable over a long period. For instance, the typical waterjet orifice, (Figure 6), used in our operations is manufactured from sapphire, and some of them (for ultrahigh-pressure work) must be manufactured from diamond in order to withstand the stress.

The abrasive waterjet, (Figure 2), utilizes the basic waterjet concept and augments it with the introduction of abrasives aspirated through a venturi section. The abrasives and water are mixed in a short mixing tube, typically made of carbide or some ceramic, and the mixture discharged toward the target. The abrasive grains act as individual single-point cutting tools similar in action to that of a sandblaster. In the case of an abrasive waterjet, the grains of abrasive are accelerated by water instead of air to a high velocity (although significantly less than the jet velocity) and impacted upon the target material. The target is both cut and worn away by the abrasives and the machining debris is flushed away by the water stream.

TEST SETUP

Our parametric testing was performed on inert materials at all three major waterjet vendors' test facilities in the United States. These facilities included Flow International in Kent, Washington; Ingersoll-Rand in Detroit, Michigan; and Jet-Edge in Minneapolis, Minnesota. Although some minor explosive testing was conducted at the Ingersoll-Rand facility in Baxter Springs, Kansas, the majority of the explosive testing was performed at the Alliant Techsystems Proving Ground (ATPG) located near Minneapolis. The proving ground test site is the largest commercial explosive test facility in the world and has complete capabilities to test and analyze explosive events.

Equipment varied slightly among the three vendors, but basically consisted of a computer-controlled, programmable 3-axis table with at least a 75 kW (100 hp) waterjet pump attached. This setup allowed exacting control and measurement of the cutting process.

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[1]Summers, D., et al., "Considerations in the Design of a Waterjet Device of Reclamation of Missile Casings," *Proc. 4th U.S. Waterjet Conference*, Waterjet Technology Association, August 1987, pp. 51–56.

Testing on explosive materials was conducted in our remote explosive machining building at the Alliant Techsystems Proving Range with an Ingersoll-Rand 29.8 kW (40 hp) *40S Streamline Intensifier™* capable of sustaining pressures of approximately 340 MPa (50 ksi) through orifices ranging in size from 0.076 mm (0.003 in.) to 0.0356 mm (0.014 in.) in diameter. The orifices were manufactured from synthetic sapphire and supplied by the vendor. The abrasives were garnet, 150 micron (100 mesh) at a mass flow rate of between 0.23 kg/min (0.5 lb/min) and 0.7 kg/min (1.57 lb/min).

The waterjet machine was located behind a standard 30 cm (12 in.) reinforced concrete blast suppression wall in the operator control station. Plumbing for the high-pressure water was run through the wall in armored conduits to minimize damage to the plumbing and to protect the workers should a failure occur in the tubing. Water was supplied from drums to prevent introduction of uncontrolled variables into the test matrix.

PARAMETERS

Our goal was to cut high-explosive projectiles safely with little or no concern for such metrics as surface finish or efficiency, which may be of significant importance to other individuals. This difference in our emphasis may explain slight differences between our work and that of other published researchers.

The parameters we identified for cutting high-explosive projectiles fall into three broad categories: first, fluid parameters relating to the flow of the water and the decay of energy; second, abrasive parameters relating to the type and amount of the cutting grains; and third, general parameters that do not fit easily into either of the preceding categories. The parameters we identified as being of importance for safety are the diameter of the impact and the velocity of the impacting jet.

Fluid Parameters

The basic parameters relating to the hydraulics of the system are the pressure of the water and the size of the orifice. Within limitations, a generalization can be made that greater pressures and larger orifices will give the fastest cutting speeds, but not necessarily the highest efficiency. The pressure of the liquid is one of the most critical parameters, because pressure has a direct relationship to velocity and for every target material there is a minimum impact velocity required in order for the material to be cut in a reasonable amount of time.[2] Below this critical impact velocity, the removal rate of material is, for reasonable purposes, nonexistent. The velocity of the fluid (Figure 7) can be approximated by the formula:[3]

$$V_{jet} \cong \sqrt{2p/\rho} \tag{1}$$

where V_{jet} = Jet velocity in m/s
p = Pressure in kilopascals
ρ = Density of the fluid in gm/cm^3

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[2]Hashish, M., "A Model for Abrasive-Waterjet Machining," *Trans. ASME J. Eng. Materials and Technology*, Vol. III, April 1989, pp. 154–162.
[3]Adapted from: Hashish, M., "Pressure Effects in Abrasive-Waterjet Machining," *Trans. ASME J. Eng. Materials and Technology*, Vol. III, July 1989, pp. 221–228.

We found that the speed of cutting is proportional to the pressure delivered by the waterjet. For this reason we elected to operate at maximum pressures on our current operations. This observation closely follows the published data for the depth of cut in other research efforts.[4, 5]

The second most important hydraulic equation is the size of the orifice which, in turn, dictates the mass flow of the water in the jet stream. The mass of water can be approximated by the formula:

$$m = \rho * A_o * V_{jet} \tag{2}$$

where m = Mass flow rate
A_o = Orifice area

Our efforts showed that the increase in orifice size significantly increased the cutting rate of the process. A drawback to increasing the orifice size is the increase in water flow consumption, which may be of concern to some projects. However, our waterjet uses only 8.2 l/min (2.2 gpm) operating at the maximum limits of the equipment. This is significantly less than that of previous systems used on washing out high explosives with a consumption rate of up to 187 l/min (50 gpm).[6] The low rate of water consumption is of particular importance to us as part of our efforts is to recycle as much water as possible. Calculations indicate that almost 50 percent of the water used can be recycled back into the system for reuse. The remainder of the water is lost through evaporation and drag-out by the abrasive disposal process.

Safety

These two parameters of jet velocity and orifice size are also the critical parameters for safely impacting high explosives. As more fully described in a separate paper presented to the Department of Defense Explosive Safety Board on our waterjet safety tests, we identified that the most serious concern was the hazards associated with the impact of high-velocity water on explosives.

Various papers have been written about the impact of projectiles on different explosives. Weiss and Litchfield[7] alone cite more than 25 papers on the topic prior to 1967. One of the most applicable works on the effects of projectile impact was that of Slade and Dewey[8] of the Ballistic Research Laboratory at the Aberdeen Proving Grounds. Andersen's[9] work became very applicable to our analysis as he identified mathematically why the impact of small-diameter, high-velocity jets of water were not initiating the explosive as data from explosive properties manuals would have suggested.

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[4]Chalmers, E., "Effect of Parameter Selection on Abrasive Waterjet Performance," *Proc. 6th American Waterjet Conference*, Waterjet Technology Association, August 1991, pp. 345–354.

[5]Hashish, op. cit., July 1989.

[6]Personal communication.

[7]Weiss, M., and Litchfield, E., *Projectile Impact on Initiation of Condensed Explosives*, Report 6986, Bureau of Mines, Pittsburgh, PA.

[8]Slade, D., and Dewey, J., *High Order Initiation of Two Military Explosives By Projectile Impact*, BRL Report No. 1021, AD145868, 1957.

[9]Andersen, W., "Critical Energy Relation for Projectile Impact Ignition," *Combustion Science and Technology*, Vol. 19, 1979, pp. 259–261.

Weiss and Litchfield showed that the critical velocity necessary for explosive initiation was very dependent on the diameter (as shown in Figure 8) of the impacting projectile and further identified that the shape of the projectile had a significant effect (Figure 9). This information was expanded upon by Andersen in the form of his equation identifying the role of the projectile diameter. His formula was given as:

$$V_i = \sqrt{A^2/d + B^2} + B \tag{3}$$

where V_i = Critical impact velocity, m/s
A = Detonation velocity / e
d = Projectile diameter, mm
B = $f / 2e$
e,f = constants for a particular explosive

Andersen identifies that for pressed TNT impacted by a cylindrical, flat-nosed steel projectile, the value of $e = 4.094\times10^5$ cm/sec and $f = 1.052\times10^{10}(\text{cm/sec})^2$.

The acoustic impedance mismatch was also identified by Andersen as being important to the initiation function. The acoustic impedance difference between steel/TNT and water/TNT is a factor of about 3.85.[10] This factor means that a steel projectile is capable of transmitting the shock front into a piece of TNT more efficiently by a factor of 3.85 over that of water.

Table 1 represents some common explosives and the estimated velocities for the 50 percent initiation point for a flat-nosed steel projectile based on the above works. In Figure 10 through Figure 14, we show the theoretical shift of critical velocities from the use of steel to water projectiles for the various listed explosives. Since each explosive has its own characteristic critical velocity for a given impact source, there will therefore be some critical impact function as the combination of orifice size and waterjet velocity, determined by the water pressure. In many cases the velocity will exceed the sonic velocity of water and act as a natural limit to being pumpable. In other cases the necessary pressure may exceed the freezing point of water at operational temperatures. Water freezes at room temperatures[11] under highly elevated pressures, as shown in Figure 15, and would provide another natural limit to a "runaway" condition.

Table 1. Projectile Impact V50 Velocities for Square Edged Projectiles.
Adapted from reference 17.

PETN	310 m/s
HMX	445
RDX	455
COMP B	1470
TNT	1745

[10]Lopatin, C., "Detonation of Explosives by Jets of Propylene Glycol Mixed with Glycerin," Alliant Techsystems Interoffice Correspondence CML 92043 to Paul Miller, February 20, 1992.
[11]Bridgman, P., "Water, In the Liquid and Five Solid Forms, Under Pressure," *Proc. Am. Acad. of Arts and Sciences*, Vol. 47, No. 13, January 1912, pp. 441–558.

The use of abrasive waterjets to cut high explosives in steel projectiles appears to be safe to at least the 0.99998 safety level. In the interest of time, additional safety related information is contained in a separate paper.

Abrasive Parameters

Choosing abrasive grains is not as simple as picking a particular hardness and then proceeding with abrasive cutting. Abrasive parameters include not only the abrasive's composition but also its physical structure, size, and mass flow rate.

Abrasive composition falls primarily into the type of abrasive used. Chemical composition, in itself, is not really sufficient to specify an abrasive grain, since one type of "garnet" abrasive may not perform like that of a "garnet" abrasive from another source. This difference may be due to slight variations in the crystalline structure, the ability to fracture into fresh cutting surfaces (known in the industry as "friability"), and the presence of contamination. The substitution of alternative materials could be a nightmare if an overzealous purchasing agent decided that he could "save" some money without consulting Engineering first.

The type of abrasives commonly used in abrasive waterjets is shown in Table 2. Most industrial users rely on garnet abrasives as the cost is low and the performance is good. The testing performed at all three vendors used "Barton" garnet, and our current operation also utilizes this material as it seems to be the most efficient and least expensive for our purposes.

Table 2. Abrasives Used in Abrasive Waterjet Cutting. Adapted from reference 13.

Abrasive	Knoop Hardness
Silicon Carbide	2500
Aluminum Oxide	2100
Garnet	1350
Silica	700
Steel Shot	600
Glass	500
Copper Oxide (Slag)	–

These abrasive grains have a typical hardness, defined by Knoop hardness numbers, which is only a partial indication of how the abrasive will behave cutting materials. Logically, the harder target materials require abrasive grains that are harder than they are. But these abrasive grains do not have to be significantly harder to be effective. Although aluminum oxide is the abrasive of choice in the grinding wheel industry and garnet abrasives are considered too soft for metal cutting,[12] the waterjet industry uses these abrasives in radically different ways. Garnet is the material of choice for abrasive waterjets, while aluminum oxide is almost a specialty item. The primary reasons why

[12]King, R., and Hahn, R., *Handbook of Modern Grinding Technology*, Chapman and Hall, NY, 1986, p. 291.

garnet is used more frequently is because garnet cuts 90 percent as well as aluminum oxide, but only costs 10 percent as much.[13] The improvement in cutting capability can be easily explained by the fact the abrasives are traveling very fast; any disadvantage garnet may have at normal grinding wheel speeds is overcome by the high velocity of the abrasive waterjet. Normally, grinding wheels operate with a surface particle speed of approximately 35 m/s,[14] while an abrasive waterjet particle is traveling at over 600 m/s.[15] At the present time, the garnet that we use for abrasive waterjet cutting only costs about $0.55/kg when purchased in multiple-bag increments.

Abrasive grain size also can be tailored for the type of material cut. We have not had any problem with cutting metals from titanium (Ti-6Al-4V) to aluminum with garnet abrasives of 150 micron (100 mesh) particle size. This particle size was suggested by the vendor and substantiated by literature as the most efficient for cutting steel.[16] Larger particles are more efficient for softer metals such as aluminum and cast iron. For those applications where surface finish may be important, the finer grain size also yields a better surface quality. One other precaution that may be worth noting is that the size of the sparks created by the impact of abrasive on steel are proportional to the size of the swarf (metal chip) removed. Our investigations have shown that, based on mathematical models available for spark ignition, the sparks we have generated too small (Figure 16) to ignite the explosive materials.[17] Increased abrasive grain size used for cutting may create larger swarf and reduce the safety margin of the process.

The mass flow rate is the last abrasive parameter that must be specified. For any given material, there will be an optimum mass flow rate that is approximately 85 percent of the maximum cutting rate.[18] This abrasive mass flow rate is chosen as it the most cost effective. Exceeding the maximum cutting flow rate reduces the cutting efficiency significantly at the cost of large amounts of abrasive material. For this reason, the logical approach should be to start off with less than ideal flow rates and gradually build up to an appropriate operating rate, rather than to jump in with the "more is better" philosophy.

Cutting Approach

We tried cutting both laterally across the projectiles, as one would do with a saw, and cutting rotating projectiles (Figure 17) like a lathe. The rotational method was significantly faster than the lateral cutting method for larger projectiles as the abrasive waterjet looses energy rapidly after penetrating the metal casing. Too fast a cutting speed on a lateral cut will prevent the jet from cutting through the opposite casing wall. An average speed for cutting 4.2 in. high-explosive mortar projectiles, loaded with Comp B, was 33 seconds by the rotational method. The lateral cutting method for the same projectile was 57 seconds.

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[13] Hashish, M., *Optimization Factors in Abrasive-Waterjet Machining*, Flow International.

[14] King, R., and Hahn, R., ibid.

[15] Chen, W., and Geskin, E., "Correlation Between Particle Velocity an Conditions of Abrasive Waterjet Formation," *Proc. 6th American Waterjet Conference*, Waterjet Technology Association, August 1991, pp. 305–313.

[16] Hashish, M., "A Modeling Study of Metal Cutting With Abrasive Waterjets," *Trans. ASME J. Eng. Materials and Technology*, Vol. 106, January 1984, pp. 88–100.

[17] von Jouanne, R., *A Computer Model for the Ignition of Methanol/Air Mixtures*, Master's Thesis, Southern Illinois University, Carbondale, Illinois, July 1987.

[18] Chalmers, E., loc. cit.

We also showed that there was very good control over the depth of cut when using abrasive waterjets on a rotating projectile. We demonstrated that the depth of penetration could be tailored to cut up to the explosive without impacting the reactive materials. However, we abandoned this delicate approach of case slitting without explosive involvement once we demonstrated that the explosive was not going to react to the effects of waterjet impact. In addition, we currently use the lateral cutting method (Figure 18 and Figure 19), which is slower in cutting speed, because the simplicity of the system and the rapidity of loading the projectile feed trays outweighed any speed advantage that rotational cutting may have had.

CONCLUSIONS

Waterjet cutting of high-explosive materials, either by plain water impact or by abrasive waterjet impact, is a demonstrated safe procedure. Parameters such as water pressure, orifice size, and abrasive size can be chosen to perform in a safe operating region, based on existing projectile impact models, for all secondary high explosives from PETN to TNT. Other parameters can be used to optimize the performance of the system and tailor it to the individual operation needs.

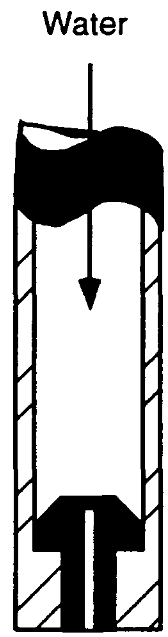

Figure 1. Waterjet

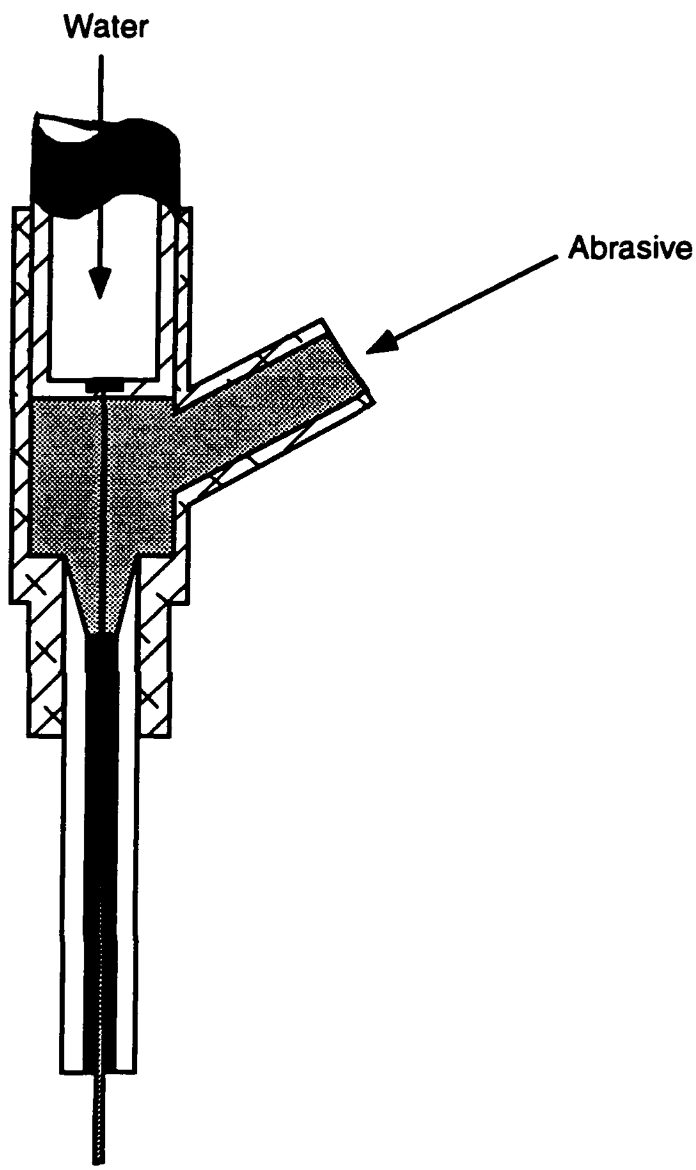

Figure 2. Abrasive Waterjet

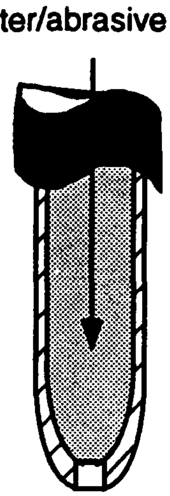

Figure 3. Slurry Jet

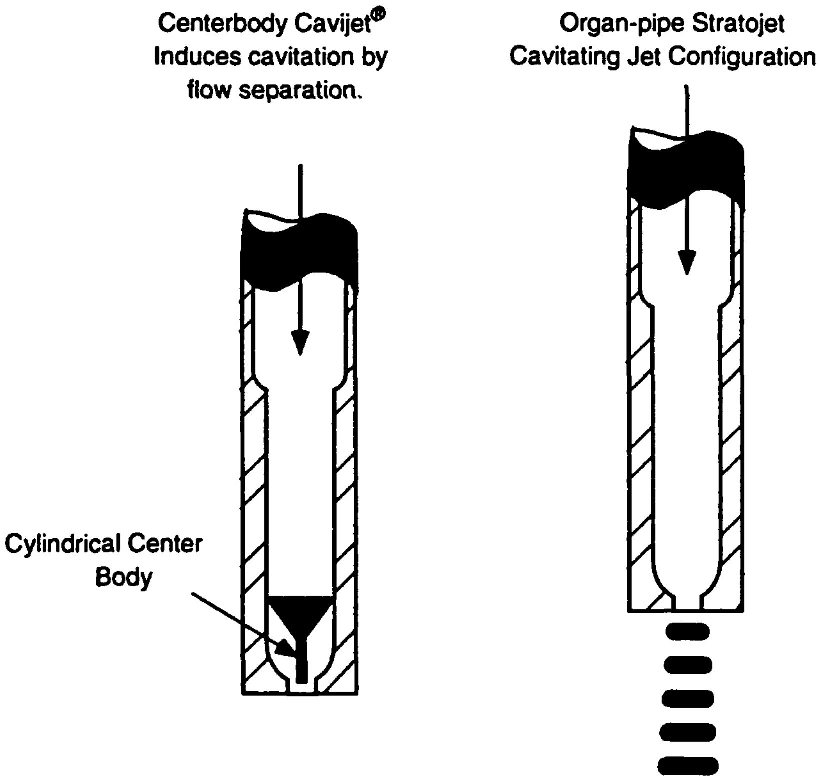

Figure 4. Cavitating Waterjets

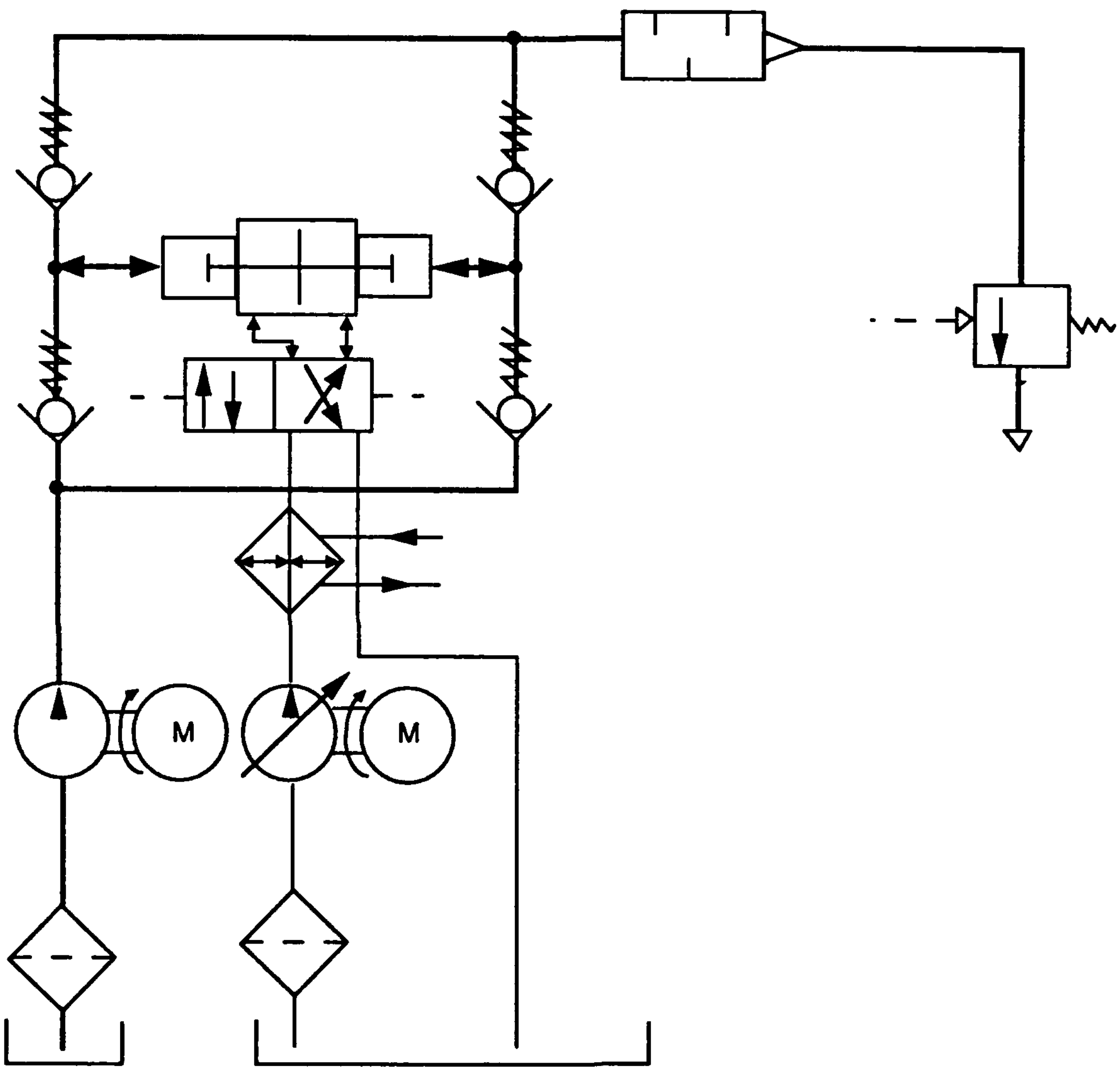

Figure 5. Waterjet Schematic

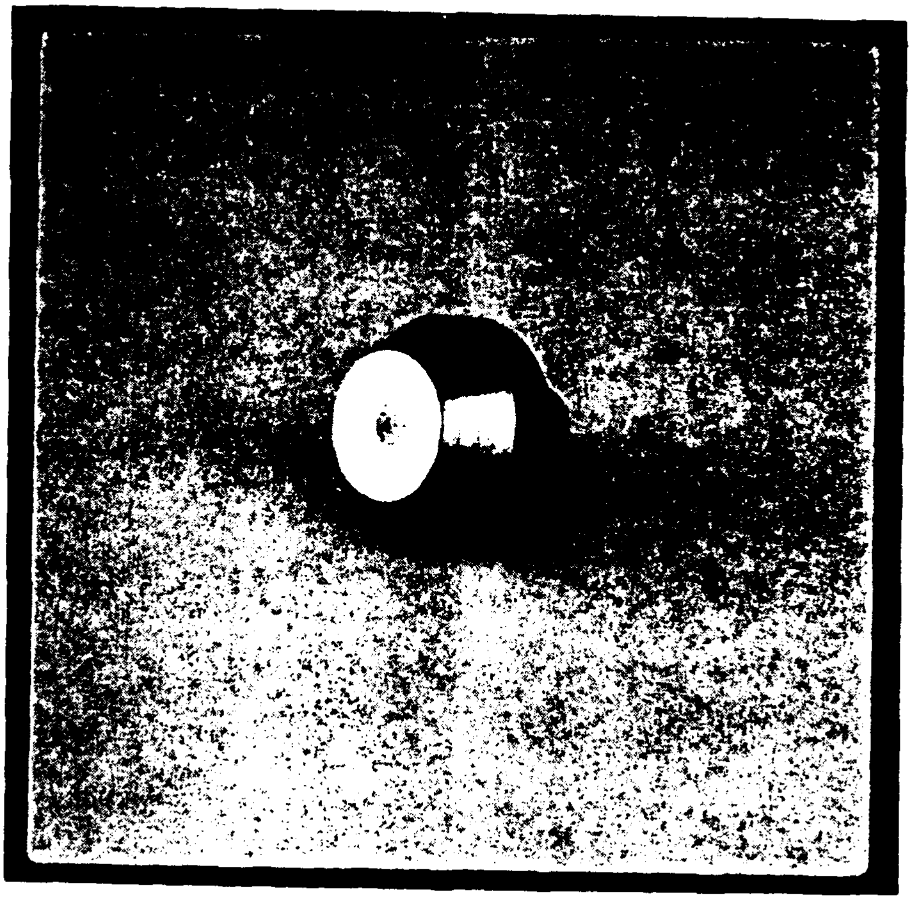

Figure 6. High Pressure Orifice

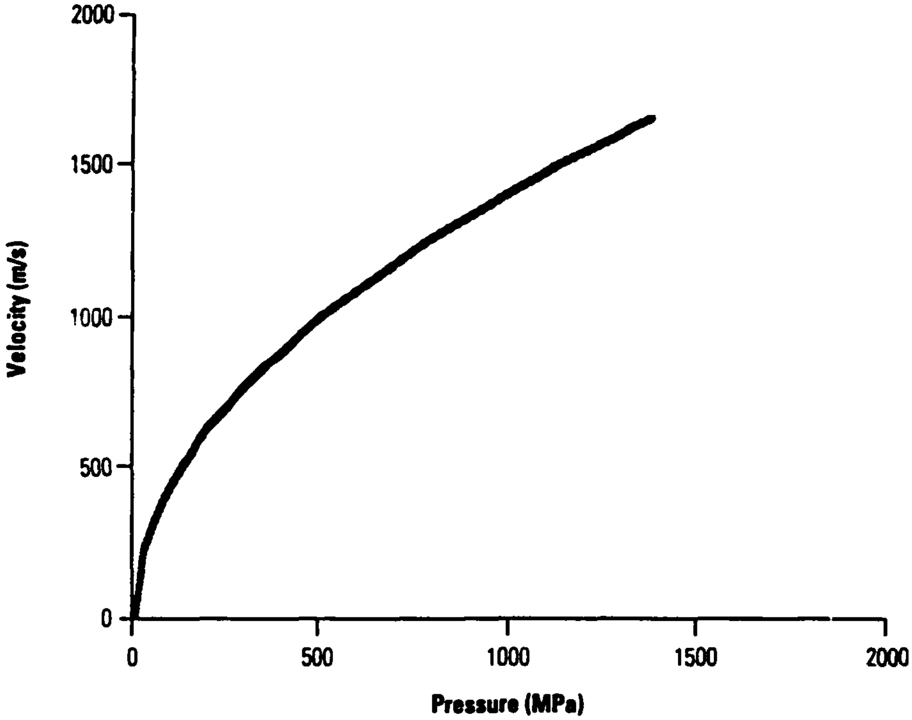

Figure 7. Velocity of Jet Stream vs. Pressure

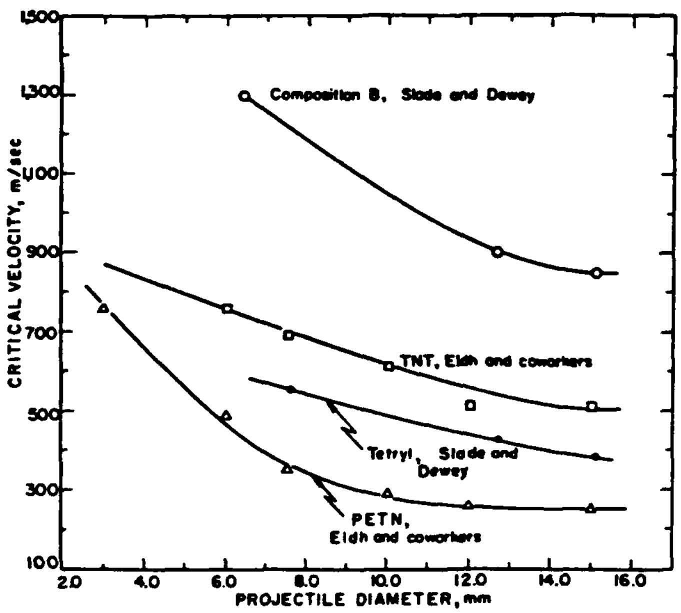

Figure 8. Critical Velocity vs. Projectile Diameter, from Bureau of Mines RI6986

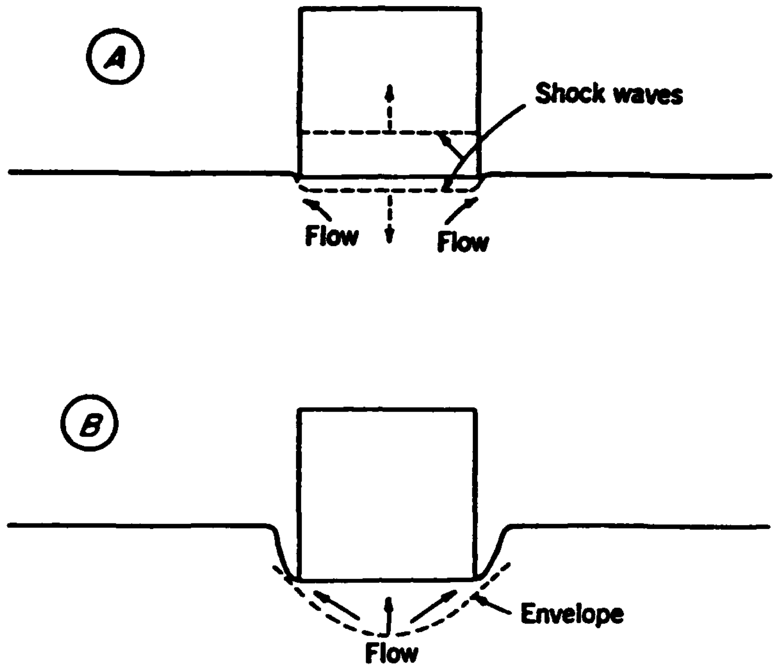

Figure 9. Projectile Impact. A: Position of shock waves in projectile and explosive and flow pattern in explosive after less than 1-mm penetration. B: Steady-state penetration of explosive by projectile. From Bureau of Mines RI–6986

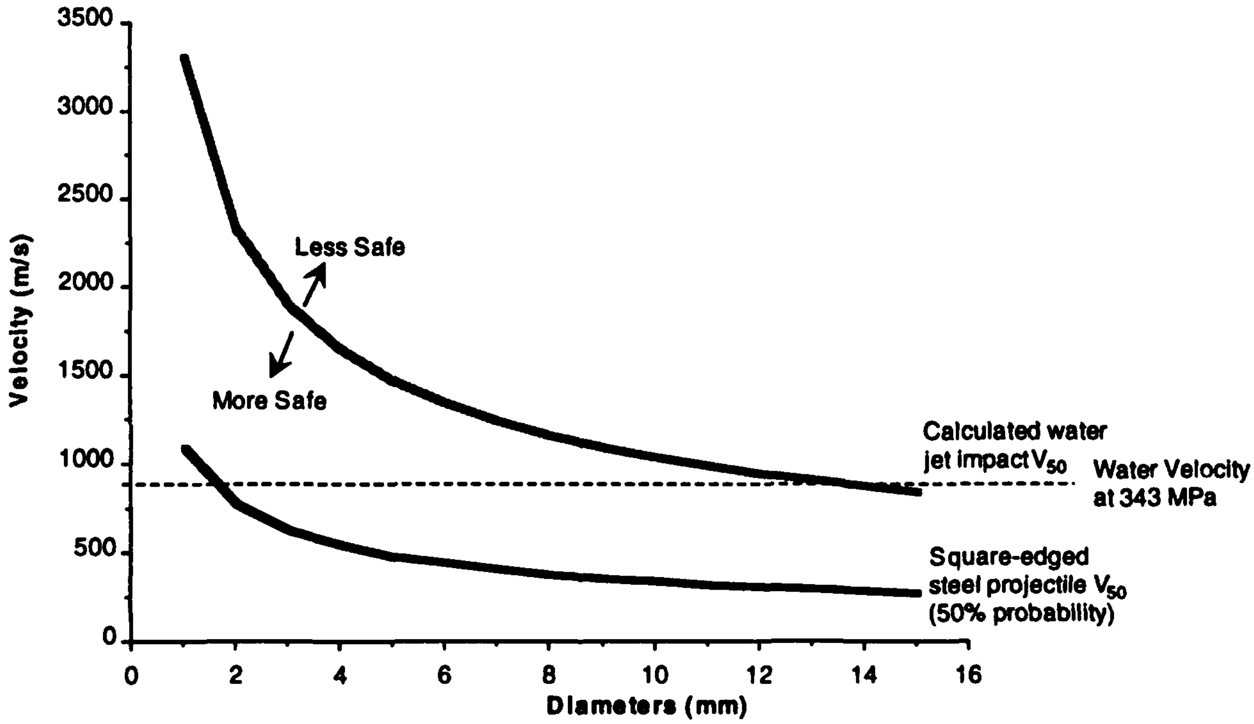

Figure 10. Projectile Impact Velocity vs. Diameter: PETN

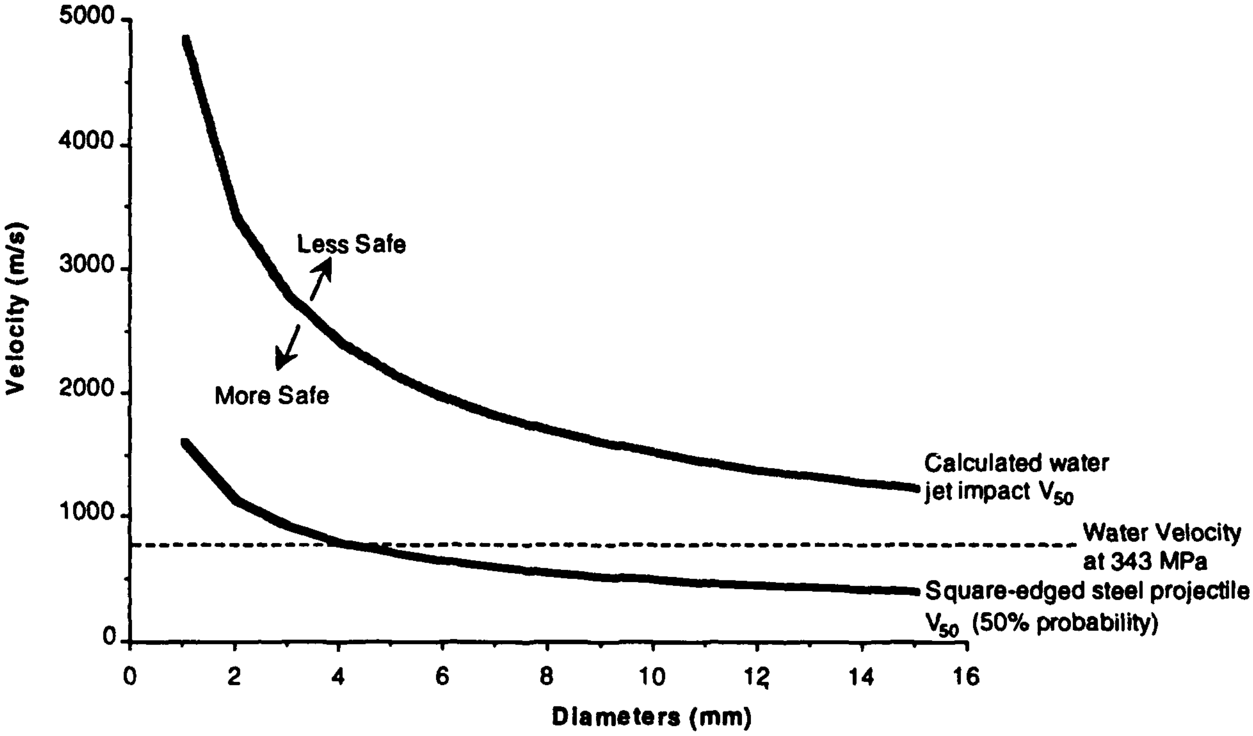

Figure 11. Projectile Impact Velocity vs. Diameter: RDX

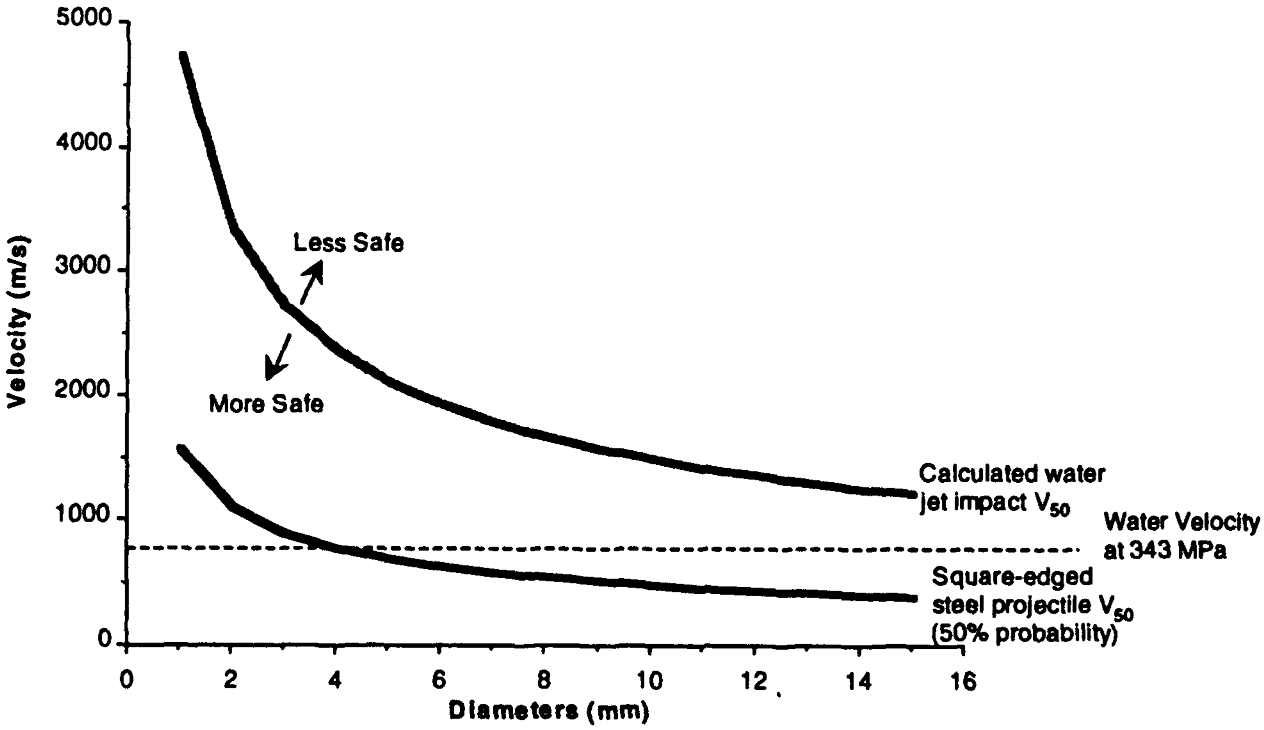

Figure 12. Projectile Impact Velocity vs. Diameter: HMX

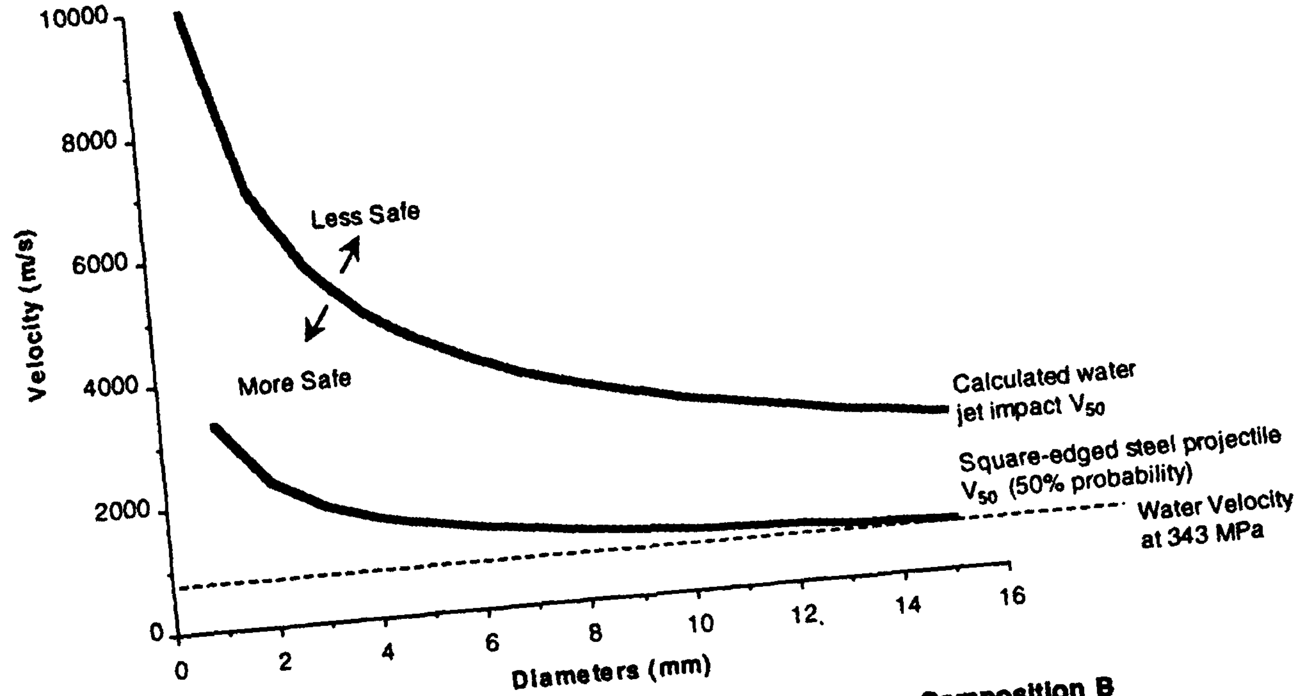

Figure 13. Projectile Impact Velocity vs. Diameter: Composition B

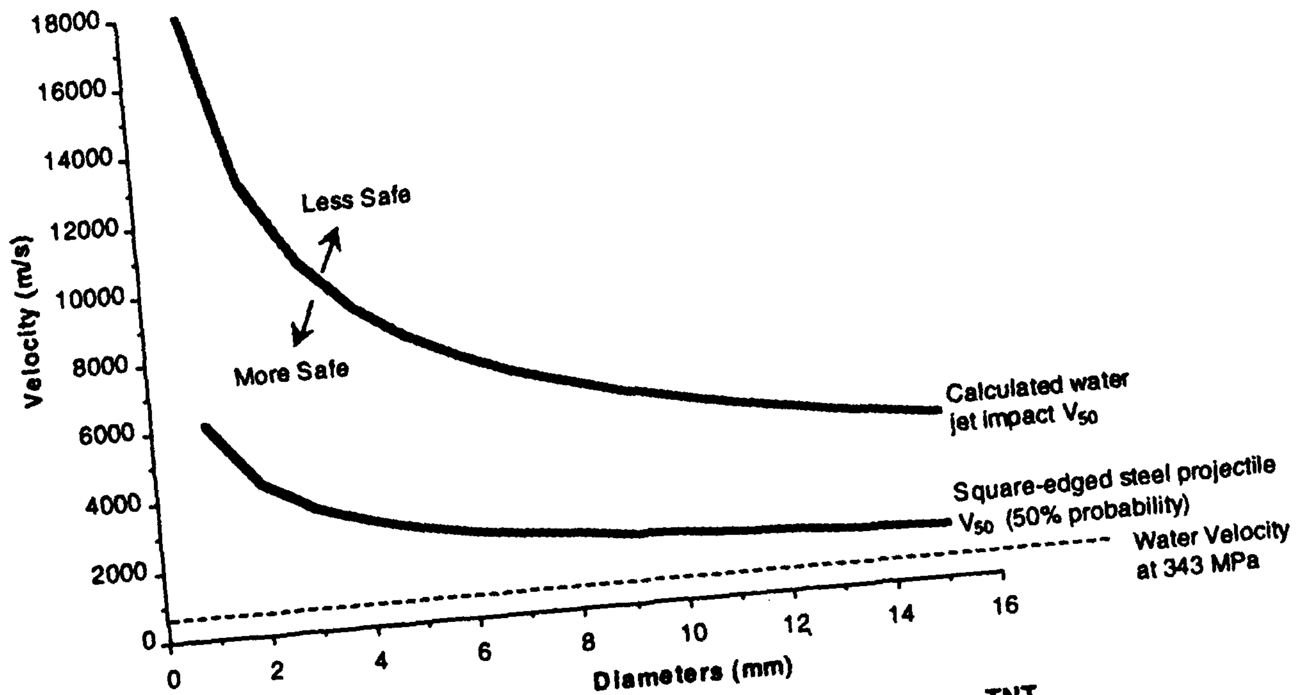

Figure 14. Projectile Impact Velocity vs. Diameter: TNT

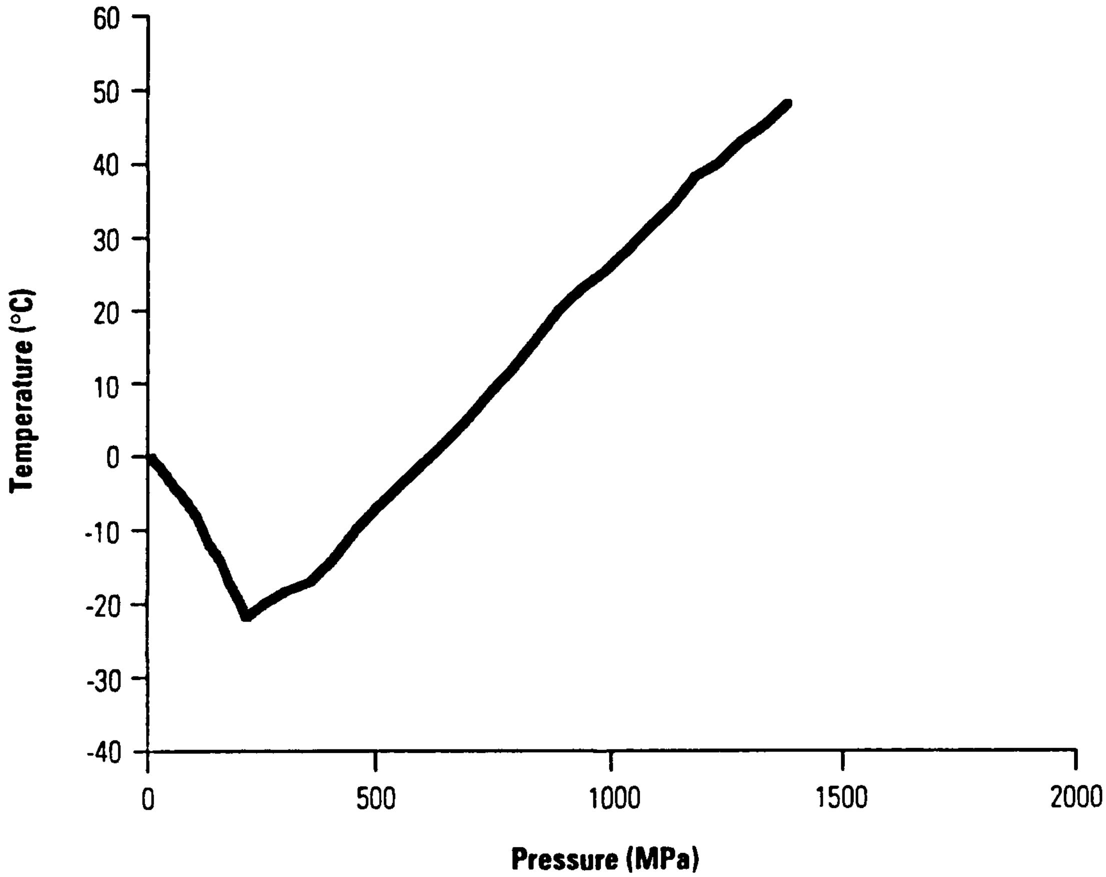

Figure 15. Freezing Point of Water vs. Pressure

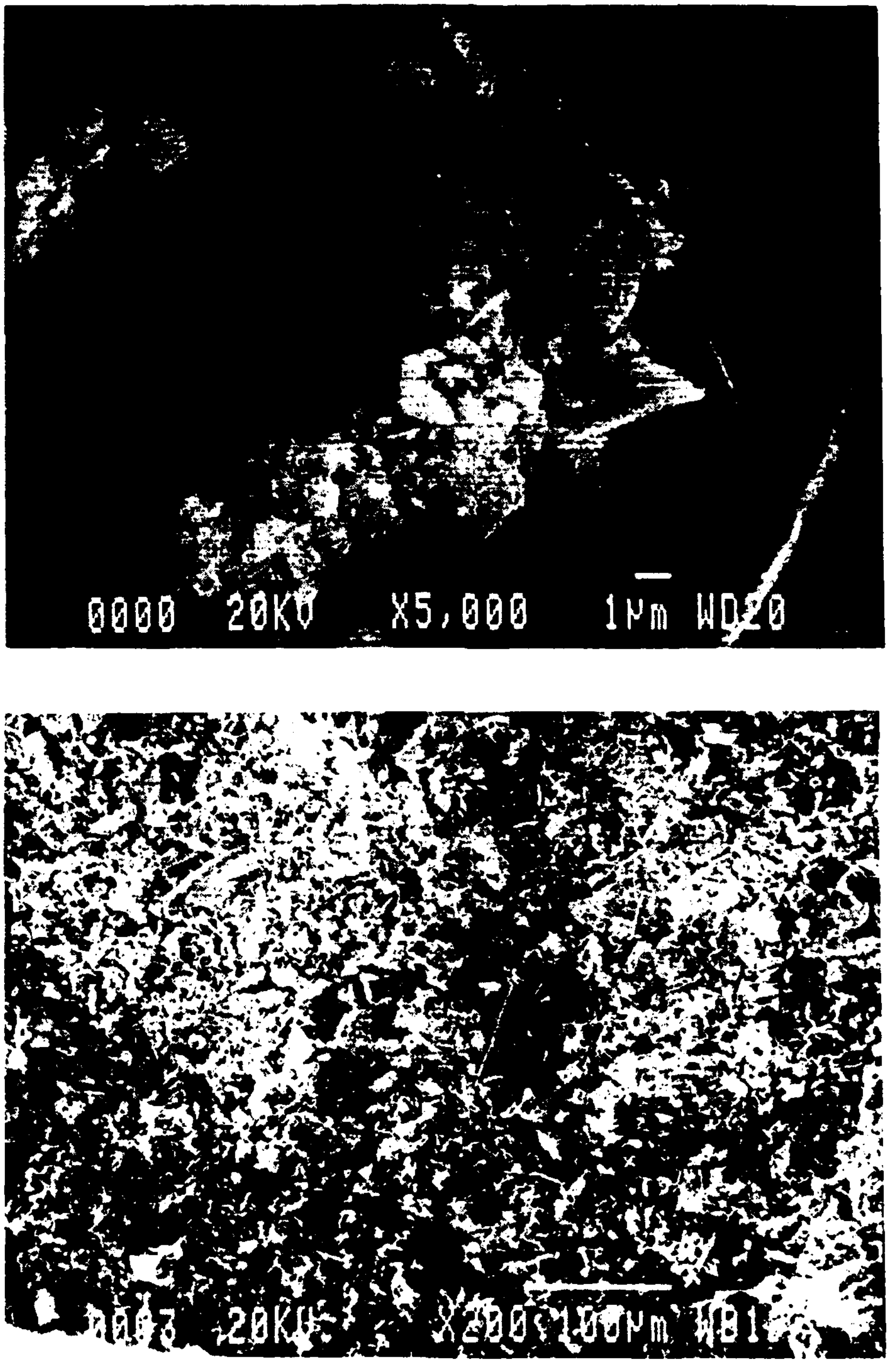

Figure 16. Typical Abrasive Waterjet Swarf

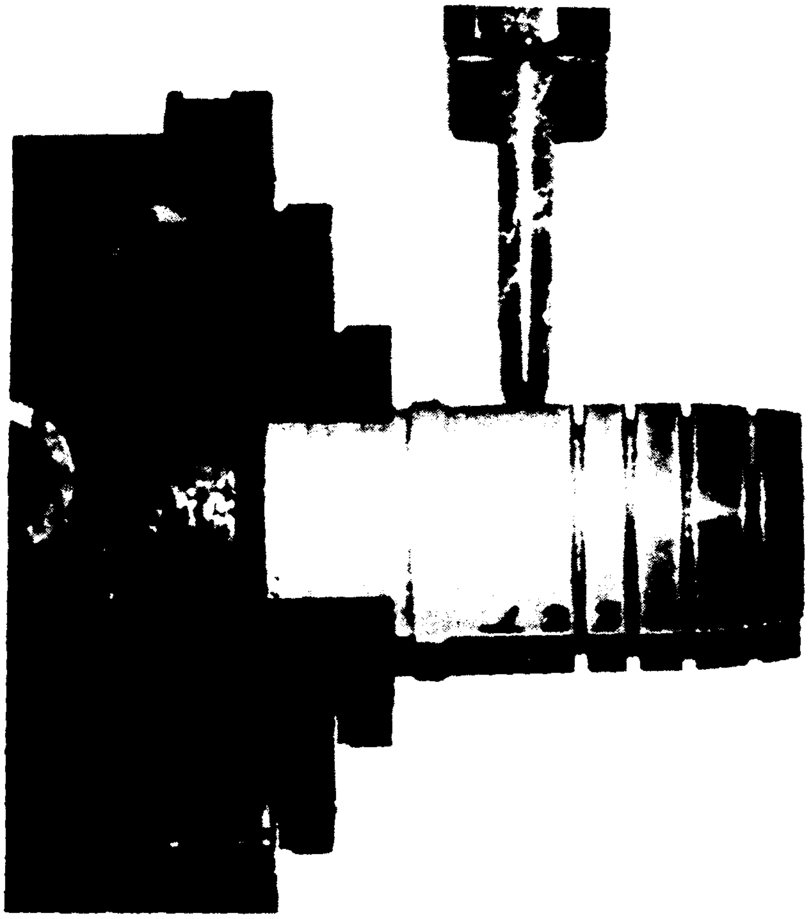

Figure 17. Rotational Cutting with Abrasive Waterjets

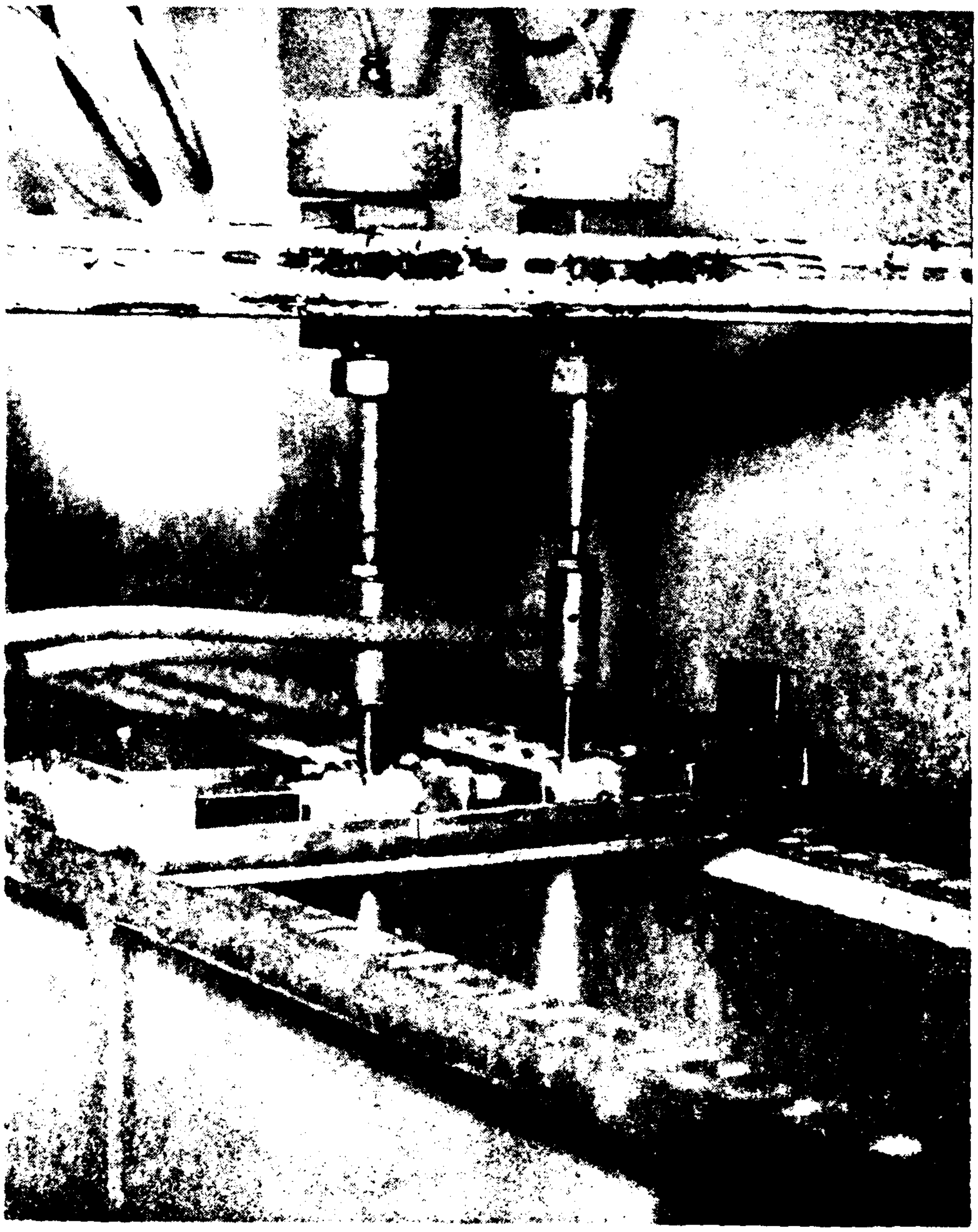

Figure 18. Abrasive Waterjet Cutting 30mm HEI Projectiles

Figure 19. Laterally Abrasive Waterjet Cut 30mm HEI Projectiles

CUTTING OF MUNITIONS AND REMOVAL OF EXPLOSIVES THROUGH APPLICATION OF WATER JET TECHNOLOGY

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ABSTRACT

Water jet technology has been used for removing explosives and propellants from large munitions and rocket motors. However, for small items where the recovery of the explosives has not been practical, destruction of the items has usually been done in the deactivation furnaces. Many munitions, because of high explosive (HE) content or shaped charge characteristics, require preprocessing by cutting/shearing/disassembly to expose the explosives or remove detonators/fuzes prior to introduction into the furnaces. Such preprocessing has traditionally been accomplished with mechanical disassembly equipment, punches and shears. This presentation covers the developmental work of the Ammunition Equipment Directorate, Tooele Army Depot, Tooele, Utah, USA, and the Royal Military College of Science, Shrivenham, Swindon, Wilts, England, in the use of abrasive water jet technology to open explosive cavities, remove detonating components, or otherwise prepare munitions items for furnace incineration. Based on work performed to date, the removal of explosives for recovery/recycling from small munitions may now be economically feasible using water jet technology.

INTRODUCTION

The origination of the present-day water jet dates back to a patent granted to Dr. Norman Franz, a professor of Forestry at the University of British Columbia, Canada in 1968. He took his idea to Ingersoll-Rand Company and they built the first high pressure water jet (approximately 50,000 psi) as a water-only cutting tool, primarily for use in furniture manufacture. This expanded into the cutting of many non-metal materials. In 1983, Flow International introduced abrasive water jet cutting, which allowed the water jet to be effectively used for the cutting of metals.

The US Army and Navy have done considerable research into the use of water jet technology for removal of explosives from munitions. Several of these projects were contracted to the University of Missouri at Rolla, where much work has been done to determine and quantify the factors of safety associated with water jet removal of explosives.

A plant has been constructed and is currently operating in Israel to wash out explosives from 105MM and 155MM projectiles. The plant uses a 5,000 psi cavitating water jet with water only as the cutting medium. Thousands of projectiles have been washed out at this plant. Although there have been many demonstrations of water jet removal of explosives, the Israeli plant is the only known production demilitarization facility we could find using a water jet to wash out explosives.

APPLICATION OF WATER JET TECHNOLOGY TO CUTTING OF MUNITIONS

While the majority of the applications of water jet technology to demilitarization have focused on explosive removal, the work of the Ammunition Equipment Directorate (AED), Tooele Army Depot (TEAD), Utah, USA, as tasked by the Ammunition Peculiar Equipment Branch, US Army Armament, Munitions and Chemical Command (AMCCOM) is primarily directed to the cutting of munitions in order to remove fuzes/detonators or to expose the explosive filler so that the munitions items can be incinerated in the deactivation furnace without detonating. At the same time, similar work has been conducted by the Chemical Systems Group, Royal Military College of Science (RMCS), Shrivenham, Swindon, England.

ADVANTAGES/DISADVANTAGES OF WATER JET CUTTING

Previous methods to accomplish the preprocessing of munitions for incineration have involved mechanical shearing, sawing, or punching to remove fuzes/detonators or to expose explosive fillers. Most of this type of equipment that has been developed is specific for a particular munition or family of munitions. The equipment is expensive and time consuming to develop, fabricate, and test. On the other hand, abrasive water jet cutting of munitions has the following advantages:

1. Versatility/adaptability - Water jet cutting is applicable to a wide variety of munitions and munitions components with minor changes to the cutting nozzles, pressures, and locations of the cuts.

2. Mechanical simplicity - The only equipment development necessary to handle the wide variety of items to be cut is the conveying equipment that delivers/removes the items from the cutting head location and holds the item in proper position for cutting.

3. Minimal equipment exposure to potential explosion - Exposure of equipment to potential damaging explosions is limited to the water jet nozzle, the conveying equipment and fixturing in the vicinity of the potential detonation.

4. Relatively low cost equipment - Abrasive water jet equipment is commercially available at a cost that is equal or less than the cost of developing a single piece of punching/shearing/sawing equipment that will handle only a small number of different items.

5. Built in quenching/cooling - The water jet provides localized cooling/quenching of materials at the cutting location. In addition, the material being impacted is immediately removed from the cutting location further lessening the propagation of any reaction in the explosives being impacted with the water jet to the surrounding explosive materials. Cooling/quenching is further enhanced if the cutting is done under water.

6. Flexible production - Production rates of cut items can be easily varied with the addition of multiple nozzles and duplicate water jet systems.

The primary disadvantage to abrasive water jet cutting is the water used in the cutting becomes contaminated with explosives, metal particles, and grit. The contaminated water becomes a disposal problem and must be considered a hazardous waste due to the presence of explosives. The ideal solution would be to filter the water for recycling in the cutting process, and handle the filtrate separately as a hazardous waste. This would greatly reduce the volume of hazardous waste that would have to be disposed of, probably by incineration. It should be noted that the filtration of the water for recycling is not a simple task since the allowable particle size in the water supply to the water jet systems used by AED must not exceed 0.5 microns. AED is investigating methods of filtration that will remove both particulates and dissolved explosives, producing water of the appropriate quality for recycling to the water jet systems.

FOCUS OF AED APPLICATION

For the investigative work done by AED, two different water jet systems were procured, one from Jet Edge Corporation, the other from Flow Systems. These two systems are of different sizes and capacities. The Jet Edge system will accommodate only one nozzle, while the Flow Systems unit is capable of powering three nozzles. Test conducted with these units are not intended to compare one system to the other. Therefore data presented in this paper, such as the time required to cut various items under different conditions, should only be compared when the same system was used.

AED's experimentation initially focused on the M42/M46 grenades, submunitions loaded in 155MM projectiles. These grenades were being punched and incinerated at Mississippi Army Ammunition Plant. Punching of these grenades to expose the explosives did not totally stop the detonations as they were incinerated. It was thought that the water jet could cut away a larger part of the grenade, exposing more explosives area such that the detonations could be eliminated in the deactivation furnace.

Inert grenades were first cut to determine the best ways and locations to make the cuts. The body of the grenade is made of 4140 steel, and the thickness of the body at the location selected for the cut is approximately 0.090 inches. Initial cuts were made by drawing the grenade beneath the water jet nozzle such that the jet would cut through the entire grenade. Garnet grit 80 mesh in size was used and it took 15 seconds to cut the grenade. A considerable amount of the simulated explosive was washed out of the grenade.

Because the effectiveness of the water jet cutting action decreases as the depth of the cut increases, it was determined that the cut would be more effective if the nozzle was positioned so that the cutting jet would be tangential to the grenade wall. This reduced the depth of the cut from the entire 1-3/8" diameter of the grenade, to approximately 0.1". To test this approach, an inert grenade was positioned in a rotating fixture with the water jet tangential to the grenade wall such that the jet would only cut through the thickness of the steel wall. The same water jet parameters, i.e., nozzle size, orifice size, water pressure, and grit size, were used as in the above test, and the grenade was rotated at 48 rpm. The water jet cut a narrow groove around the grenade body until the fuzed top of the grenade separated. The time to cut the grenade was approximately 8 seconds, and the explosive filler was only slightly eroded. Several grenades were cut in this manner and the time to cut each grenade was very repeatable, about 8 seconds.

Of concern in these tests was the sparking that resulted when using the garnet grit to cut the steel grenade casings. Since sparks are not normally considered compatible with explosives, additional tests were conducted using "Copper Blast" grit which is a grit produced from the slag left over from copper smelting operations of Kennecott Copper Corporation. The sparks produced were not significantly decreased, but the cutting time increased from 8 seconds for the garnet grit, to 15 seconds for the "Copper Blast" grit. It is of interest to note that in tests conducted by RMCS, the sparks produced in water jet cutting appear to be "cold" sparks with insufficient energy to ignite explosive concentrations of hydrogen in air. This reduces the concern of the presence of such sparks when cutting explosives filled munitions.

ADVANTAGES/DISADVANTAGES OF CUTTING UNDER WATER

The next tests compared the cutting rates above and under water. Grenades were rotated at 28 rpm maximum. Using the Jet Edge system and the same water jet parameters for each test, it took approximately 15 seconds to cut a grenade above water, and 17.5 seconds to cut a grenade below water. Although the cutting time underwater was slightly longer, it appears to offer the following advantages over open air cutting:

1. Noise is greatly reduced.
2. Overspray and splatter are practically eliminated, thus confining debris to the water tank.
3. Water in the tank essentially eliminates sparking when cutting metal. Any sparks created are short lived due to the rapid quenching of the surrounding water.

The disadvantages of cutting under water are as follows:

1. It is difficult to observe and hear what is happening during the cutting. When cutting in open air, the operator can hear when the water jet has finished the cut by the change in sound. This is not as apparent under water.
2. Cavitation may be created when the high pressure stream encounters the water in the reservoir, although this may not be of much concern in this application.
3. More components of the holding/conveying fixtures will need to be sealed against entry of water.

Evaluating the advantages and disadvantages, it appears that the advantages to underwater cutting greatly outweigh the disadvantages, and will be pursued further by AED.

Tests were then conducted with live M42/M46 grenades loaded with Composition A5 explosive. 200 grenades were cut in open air without incident. The grenades were incinerated in the deactivation furnace where two grenades still detonated, even though the entire top of the grenade had been removed to expose the explosive filler. Since the exposure of more explosive filler area failed to eliminate detonations of the grenades in the furnace, it was decided to add another station to the process where the explosive filler could be removed by non-abrasive water jet. It was demonstrated that a 1 second blast of the water jet removed the explosive filler which could be incinerated separately in the furnace or filtered from the water for recovery/recycling.

FOCUS OF RMCS APPLICATION

RMCS has not only demonstrated water jet cutting of various munitions, but has developed modifications to the conventional

method of introducing abrasives into the water jet stream that permits use of lower water pressures, increases the nozzle life, and increases the effective cutting distance with reduced spread of the water jet stream. RMCS determined that the normal method of adding abrasives to the water jet stream at the nozzle introduced considerable air into the stream which decreases the distance that the water jet stream holds its shape, resulting in a corresponding decrease in effective cutting distance. Also, the turbulence in the nozzle caused by the air and grit entrainment resulted in erosion of the nozzle orifice, reducing life of the nozzle.

As a result of their evaluations, RMCS concentrated on modifying the method of adding abrasives to the high pressure water. Figure 1 diagrams the RMCS water jet system which they have patented and market under the trade name DIAJET. A concentrated abrasive slurry is pumped into a supply tank which is pressurized by the high pressure water jet pump. A slight restriction in the water jet line produces a slightly higher pressure in the abrasive slurry tank such that the slurry can be introduced into the water jet line at the appropriate rate through a control valve to produce the desired abrasive concentration in the water jet. This process results in the introduction of abrasive into the water jet without also adding air. Since the water jet stream as it exits the nozzle has no entrained air, the stream retains its shape longer, which results in an increased effective cutting distance. Without the entrained air, the pressures required for cutting can also be significantly reduced. Most of the RMCS cutting of munitions has been accomplished at 5,000 and 10,000 psi.

Another significant development of RMCS is in the patented nozzle design. The nozzle holder shown in Figure 2, has a separation zone which necks down such that the heavier abrasive particles in the water jet are forced to the center of the water jet stream. This creates a film of water around the abrasive such that the abrasive does not contact the nozzle surface as the water jet/abrasive mixture enters the acceleration zone and exits the nozzle. Nozzle life is greatly increased as a result.

Another advantage to the reduced water pressure required for cutting is that flexible rubber tubing/hose can be used between the high pressure pump and the nozzle. Hose length is not critical, making long hose runs possible. This is very desirable in locations such as England where unexploded ordnance is found routinely and the water jet can be used to remotely remove fuzes and otherwise disarm munitions.

OTHER POTENTIAL APPLICATIONS TESTED

Both AED and RMCS have conducted experiments with cutting a variety of munitions. AED cut an inert 90MM projectile in 3 minutes 10 seconds by rotating the projectile under the water jet nozzle positioned off-center on the round so that it cut only to a depth of 5/8". The water jet cut the projectile like a lathe,

cutting a greater depth each rotation. This method resulted in only minor erosion of the simulant explosive filler. RMCS has cut munitions up to 5 inches in diameter without rotation because their system can cut greater thicknesses without jet deterioration. They also experienced minor erosion of the explosives.

Another potential application of water jet cutting was demonstrated by AED with the cutting of an inert M55 rocket to separate the motor from the warhead. The cut was made through the fiberglass shipping and firing tube and the steel motor casing in the area of the void in the motor section above the propellant grain. The cut was completed in approximately 45 seconds. Water jet cutting of M55 rockets to separate the motor from the warhead in the event the propellant stability becomes suspect, has the advantage of minimizing handling of the rocket, which would include removing the motor ignitor shunt if the rocket has to be removed from the firing tube for mechanical disassembly. This concept has been accepted by the Army for further process and equipment development as the method to use if it becomes necessary to remove the propellant before the rockets can be destroyed in the Chemical Stockpile Disposal Plants, construction of which has not yet started, except for the Tooele site.

CONCLUSION

Experimentation with water jet cutting of munitions and explosive removal is continuing at AED and RMCS. Based on the past successes, it is felt that the advantages and benefits of using water jet technology for these applications, give it the potential to become one of the most widely used munitions preprocessing methods for demilitarization by explosives removal or incineration.

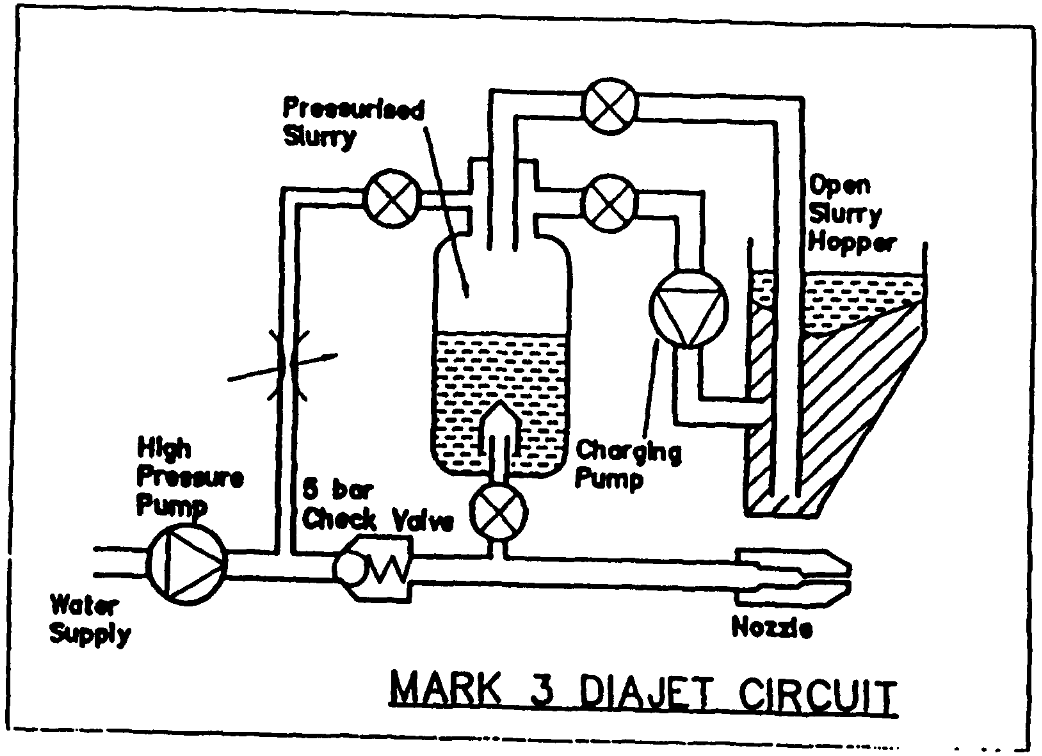


FIGURE 1 RMCS WATER JET SYSTEM

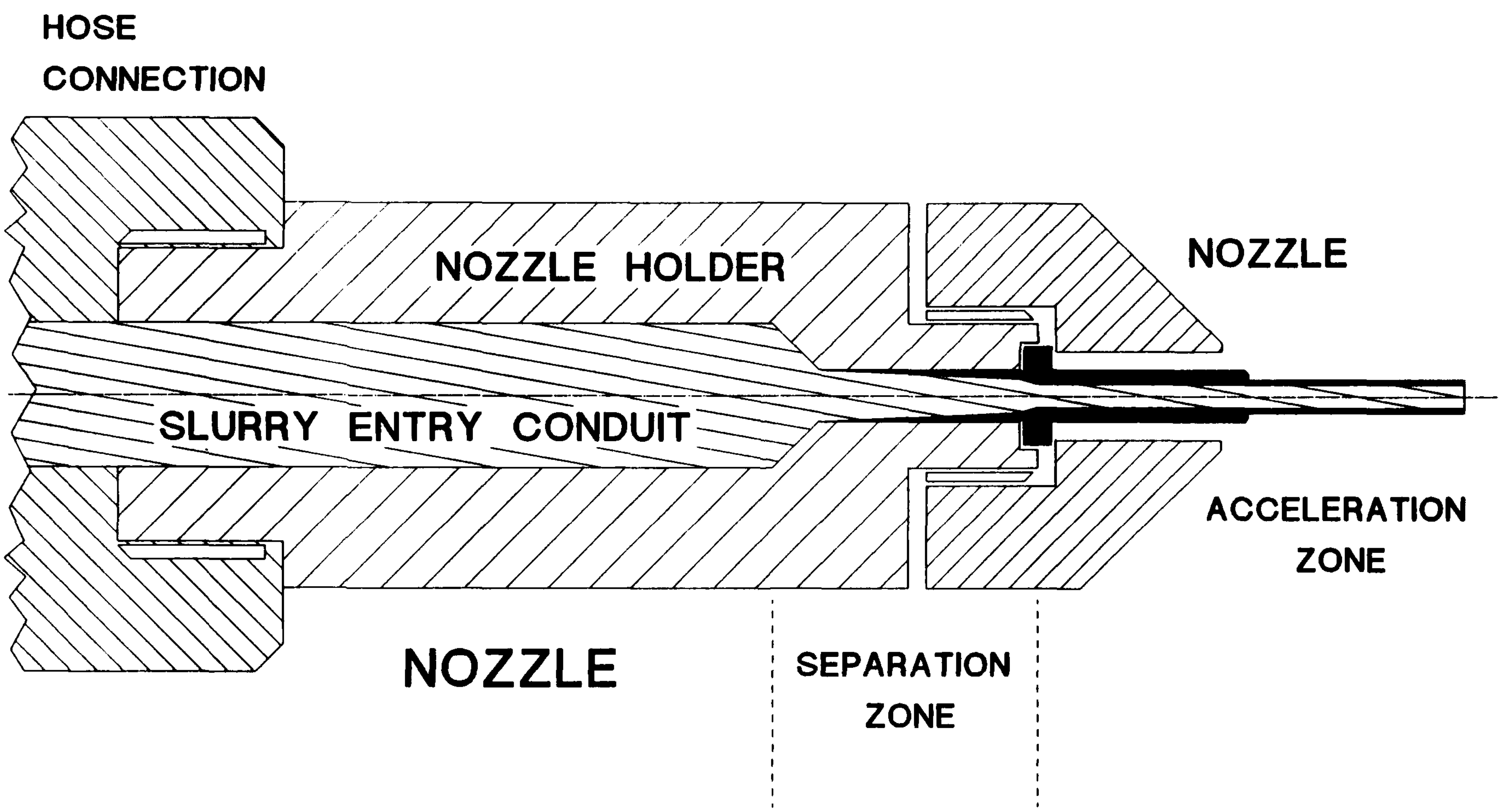
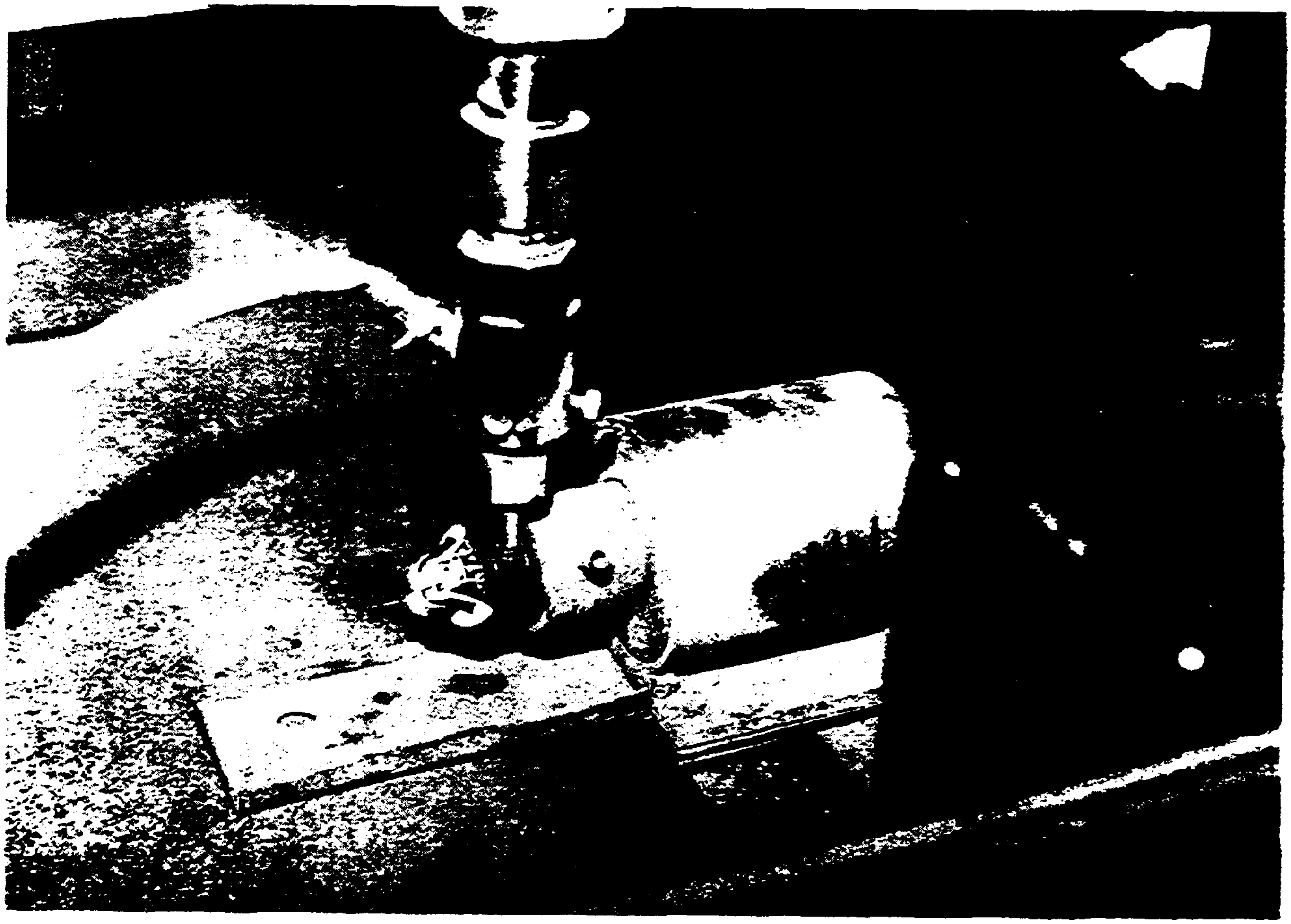
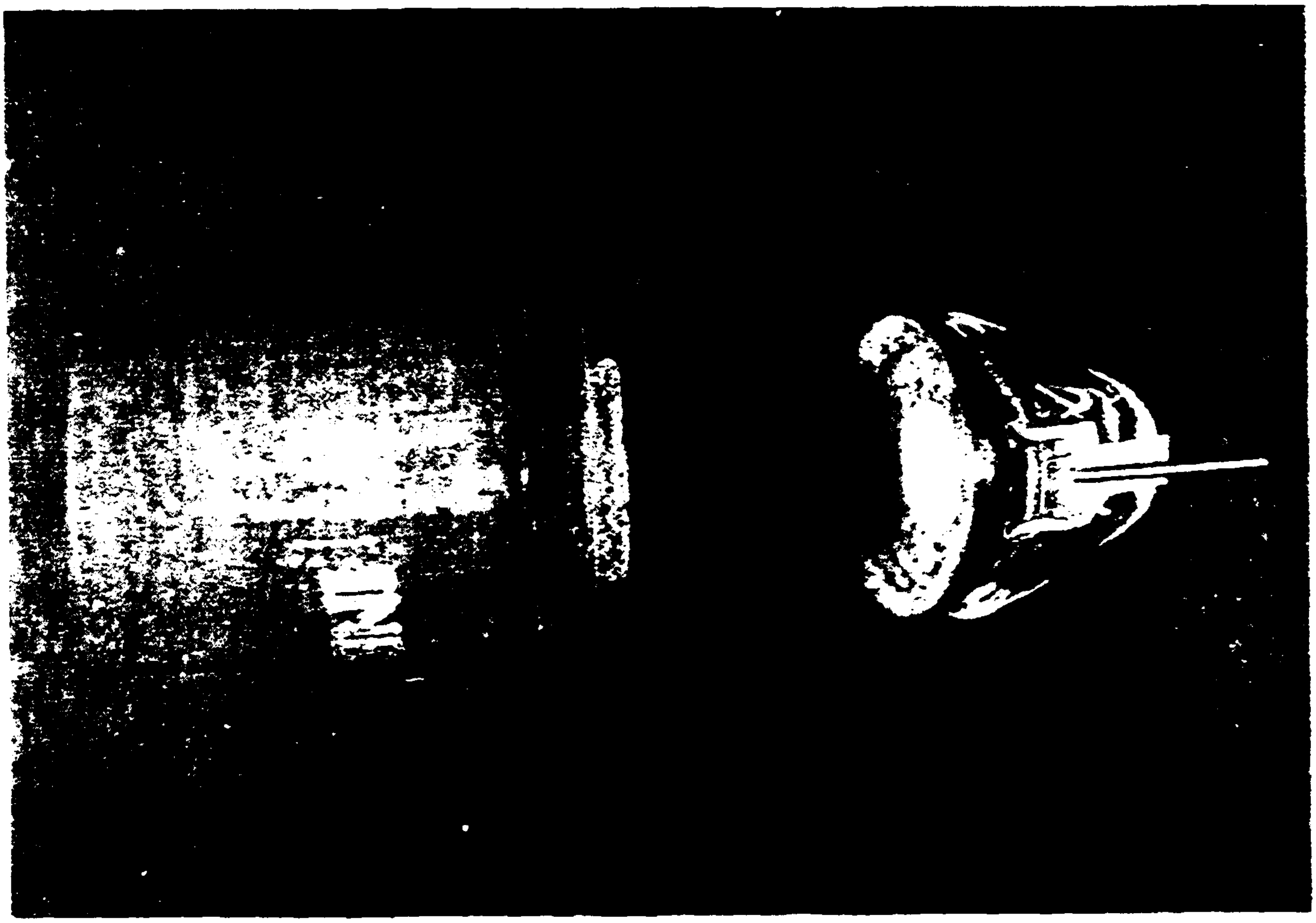


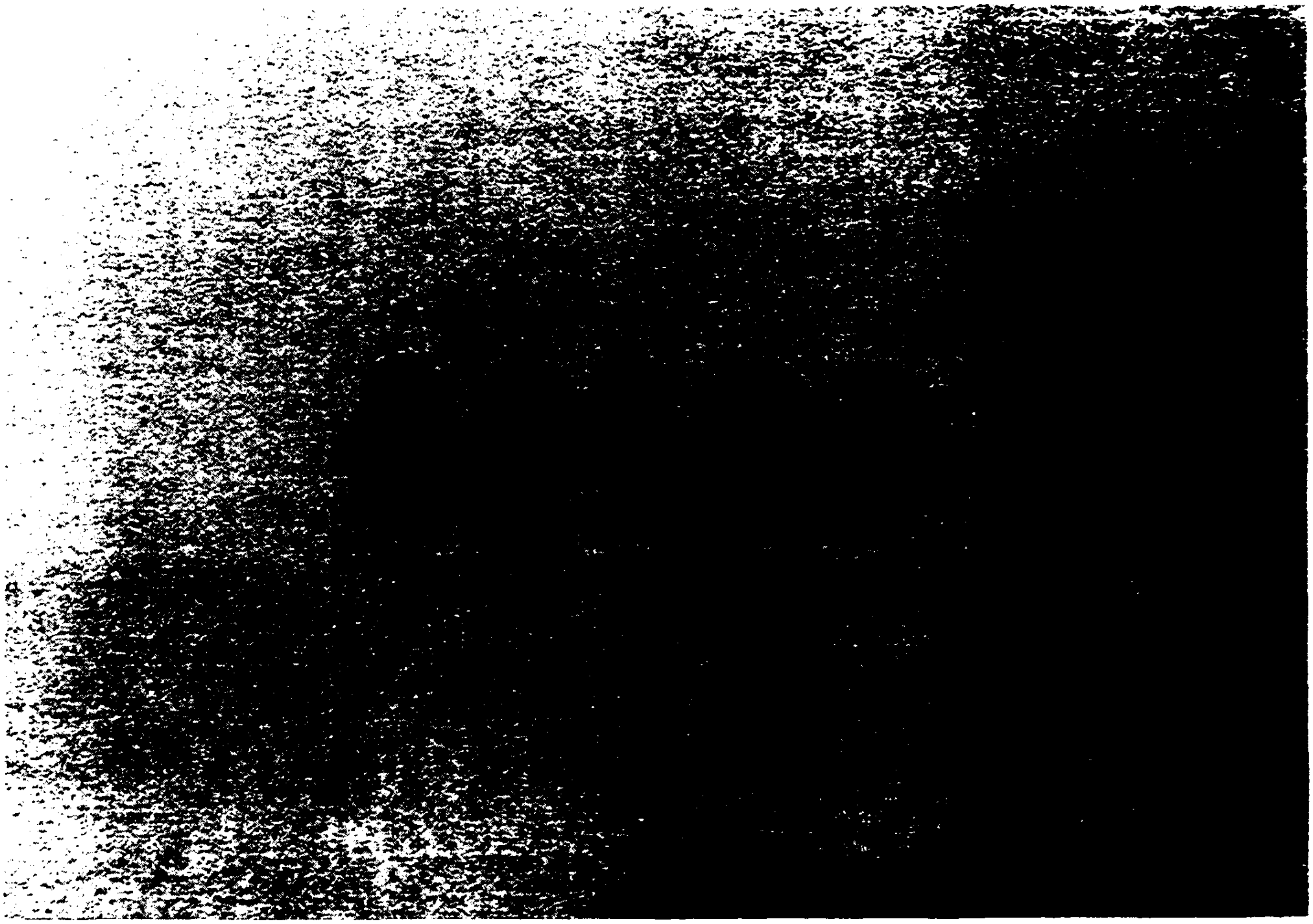
FIGURE 2 DIAJET NOZZLE



Positioning of water jet nozzle over M42 grenade for cutting. Grenade is in fixture that rotates grenade under nozzle so that cut is made only through steel casing.



M42 grenade cut with water jet removing fuzed top of grenade. Notice how little simulant explosive is eroded.



M42 grenades after being cut and incinerated in the deactivation furnace.

Inert 90MM projectile cut by water jet in 3 minutes 10 seconds.

Inerted M55 rocket cut with water jet in 45 seconds to demonstrate capability to separate motor from the warhead. Cut was made through fiberglass shipping and firing tube, and steel motor casing in void above the top of the motor grain.

Current Progress on the Use of Waste Energetic Materials as Fuel Supplements for Industrial Combustors

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ABSTRACT

An alternative disposal technology for waste energetic materials which has demonstrated potential for future applications at military installations is the reuse of these materials as a supplemental fuel for industrial combustors. The Department of Defense, over time, has accumulated a significant stockpile of waste energetic materials which requires disposal. The current disposal options, incineration, open burning and open detonation, are either cost prohibitive or under environmental scrutiny. An alternative disposal technology which shows promise is the reutilization of these energetic material;s as a supplemental fuel. Initial studies have indicated that it is feasible and economical to utilize the energy content from explosives and propellants to supplement fuel oil in industrial boilers. Significant progress has been made on the development on the process to use explosives as a supplemental fuel. Previous pilot scale tests and initial tests from a pilot scale demonstration at Hawthorne Army Ammunition Plant, Hawthorne, Nevada, have clearly demonstrated that explosives fuel oil mixtures can be safely fired into a standard industrial boiler. A state-of-the-art pilot scale system was designed and constructed for solvating and mixing explosives with fuel oil and firing the resultant mixture into a into a boiler to generate steam. Future tests are scheduled to increase the quantity of explosives in the fuel mixture and obtain additional process design information for full scale implementation. A feasibility study and a hazard analysis to determine the propagation potential for propellant/fuel oil slurries has recently been completed. The current progress and background with emphasis on the safety aspects on the use of explosives and propellants as a supplemental fuel are described.

INTRODUCTION

The Army, as the sole Department of Defense manager for explosives, is currently evaluating and developing safe,

environmentally acceptable, alternative disposal and reuse technologies for it's stockpile of waste energetic materials. Waste energetic materials are propellants, explosives, and pyrotechnics and are commonly referred to as PEP. Unserviceable PEP materials are generated from the manufacture of PEP materials, assembly of munitions and demilitarization of obsolete conventional munitions. It is estimated that approximately 2.5 million pounds of scrap and off-specification energetic materials are generated each year[1]. In addition, there were an estimated 200,000 short tons of conventional munitions requiring demilitarization in 1990.

The disposal alternatives for these unserviceable PEP materials are open burning/open detonation (OB/OD) and incineration[1]. OB/OD is the preferred method of disposal, however it's use requires a Resource Conservation and Recovery Act (RCRA) Subpart X permit and due to environmental concerns, OB/OD is only allowed on a case by case basis. Incineration of energetic materials is uneconomical. To safely burn these materials, energetic materials are mixed with 75% water to form an energetic material/water slurry. The water is required to prevent detonation propagation during the handling and feed process. The addition of water increases the amount of fuel required to incinerate the energetic materials. Although OB/OD and incineration are acceptable disposal technologies, neither technology takes advantage of the energy content of these materials.

The U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) began investigating the feasibility of reusing the energy content from waste energetic materials to produce steam and/or electricity in 1984. Since explosives are a major waste energetic material in the U. S. Army's inventory, the USATHAMA began investigating the potential of using trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), and Composition B (40% TNT and 60% RDX) as a supplemental fuel.

BACKGROUND ON THE USE OF EXPLOSIVES

FEASIBILITY STUDY

In 1985, the Oak Ridge National Laboratory conducted a study to determine the feasibility of utilizing energetic materials as a supplemental fuel for industrial combustors [1]. This study examined the economics under different scenarios in which energetic materials might be economically used to generate steam and/or electricity in industrial combustors. The study also compared the costs of using

energetic materials to the currently available disposal methods. The conclusion of this study determined that the cofiring of explosives could be economically competitive if existing oil-fired combustors at military production and demilitarization facilities were used without major combustor modifications.

PARTICLE SIZE REDUCTION

Since TNT and RDX are relatively insoluble in fuel oil, an explosives supplemented fuel oil would have to be burned as a slurry. Efficient burning of fuel oil requires atomization before combustion. Since standard oil burner designs use small holes to effect atomization, the energetic materials would have to be reduced to an acceptable size. Conventional techniques for energetic material size reduction, employing the grinding of the materials in water, results in a mean particle size to large for use with standard oil burners. A concept was proposed to reduce the particle sizes of TNT, RDX and Composition B by dissolution in a solvent such as acetone or toluene.

COMPATIBILITY, HANDLING CHARACTERISTICS, AND REACTIVITY

A second major area of investigation in the development of this technology was the evaluation of potential safety issues associated with the handling and burning of various mixtures of explosives, solvents, and fuel oil [2]. Testing was conducted to determine the chemical compatibility and stability, handling characteristics, and reactivity of the energetic-fuel mixtures. The chemical stability of explosives and fuel oil were determined by differential thermal analysis, vacuum thermal stability, and accelerating rate colorimetry. Results indicated that the fuel oil-energetic mixtures were chemically compatible. In addition, laboratory tests indicated that explosives/fuel oil mixtures could be handled safely.

The major areas investigated in handling energetic-fuel mixtures were the solubility of the energetic in the fuel, the viscosity of the energetic-fuel mixture, the energetic particle size distribution, and potential for nozzle plugging [2]. To achieve effective atomization in an oil burner the viscosity of the resultant energetic-fuel oil mixture should not exceed 30 centistokes. The results of the solubility and viscosity tests did not establish the upper boundary limits for the composition of the energetic-No. 2 fuel oil mixtures. The optimum compositions would have to be dictated by the propagation tests.

Bench-scale studies to determine the particle size limitations of the slurry using standard burner nozzle configurations indicated that no plugging problems should

arise with the use of acetone or toluene for particle size reduction at the concentrations of concern. Although plating tests indicated a thin film of TNT was deposited on the surfaces of stainless steel when exposed to mixtures of TNT and fuel oil for at least 6 months, the surface buildup is easily removed by flushing with warm acetone.

Propagation tests were performed to establish the propagation of detonation characteristics of solvent solutions and fuel oil slurries of TNT and RDX [2]. These tests were run to determine the maximum allowable concentrations of explosives that can be safely transported in process piping. Both static and dynamic tests were performed. Static tests were conducted in a 2 inch horizontal pipe in which the explosives were allowed to settle out for 8 hours. Mixtures of TNT-toluene showed no propagation in both static and dynamic tests up to 65 wt.% TNT. Under dynamic tests, RDX concentrations up to 15 wt.% did not propagate a detonation. RDX/toluene mixtures, however, did propagate a detonation under static testing at >5.3 wt.% RDX. This was due to RDX particles settling and forming a trail on the bottom of the pipe. The limitation on the concentrations of explosives that can be used to supplement fuel oil is the quantity required for static propagation of detonation.

Although the limited solubility of RDX in toluene causes concern for the potential of burner nozzle plugging, toluene was selected as the solvent of choice for future pilot demonstrations. Toluene has a heating value and cost comparable to fuel oil. If acetone where used, for economic reasons nearly all of it would have to be recovered by evaporation before the mixture was fired into the combustor.

PROTOTYPE PILOT-SCALE DEMONSTRATION

In 1987, the first pilot scale demonstration on the cofiring of explosives/fuel oil mixture was conducted at Los Alamos National Laboratory using a 300 kW (10^6 BTU/hr) combustion chamber [3]. The combustor was operated using fuel oil supplemented with TNT, RDX and Composition B. The pilot scale system was designed upon the fuel blending and feed requirements and safety issues described above. Although the tests were discontinued because of equipment failure, a sufficient amount of data were obtained which clearly showed that explosives can be safely cofired with fuel oil. The data indicated that explosives could be cofired using off-the shelf equipment, the process would meet present and anticipated environmental requirements and several design and operational changes were necessary.

ECONOMIC ANALYSIS OF USING EXPLOSIVES

Myler described the economics of cofiring TNT and Composition B by comparing it to an industrial boiler using No. 2 fuel oil [6]. A supplemented fuel containing 55% No. 2 fuel oil, 15% TNT, and 30% toluene was compared using a 20 MBtu/hr boiler. This is the standard size package boiler used at military installations. Operating at 80% efficiency, it was estimated that 480 short tons/year of waste TNT could be disposed of using this technology. In addition, the analysis indicated that as fuel costs rise, the use of waste explosives as a fuel supplement would be profitable. The break even point was a cost for No. 2 fuel oil of $0.83 per gallon with a constant toluene cost of $0.93 per gallon. Since this study, the fuel oil prices have risen above this point which implies there would now be a net profit for burning the supplemented fuel at the ratios previously described.

PILOT-SCALE FIELD DEMONSTRATION USING EXPLOSIVES

EQUIPMENT DESIGN AND PROCESS

In 1989, a state of-the-art pilot scale system was designed and constructed for mixing explosives with fuel oil and firing the resulting mixture into a standard industrial boiler to generate steam [4,5]. The test equipment was designed to meet strict safety standards involved in the handling of explosives and volatile solvents. The major process equipment items in this pilot scale system are the explosives dissolving system, the fuel/explosives blending tank, the boiler and steam vent system and boiler management system. A prototype explosives dissolving and blending system was designed to dissolve the explosives in solvents, mix the solvent-explosives mixture with fuel oil, and feed the resultant mixture to the boiler system. The dissolving tank and blending tank were constructed of stainless steel. There are two dissolving tanks with air actuated mechanical mixers. These tanks were indirectly heated using steam from the boiler. The blending tank was not steam heated and used an air diaphragm pump to mix the explosives solution with the fuel oil and feed the resultant mixture to the boiler.

The boiler selected for the pilot scale system was a standard Cleaver Brooks Model M4000, 2 million Btu/hr, water tube-type boiler. This size boiler is one tenth the scale of the majority of boilers used at Army facilities. This standard boiler was modified to meet the required electrical specifications and the burner assembly modified with three burner assemblies for the propane pilot, the fuel oil, and the explosives-fuel oil solution. The burners were sonic atomizer type nozzles. The boiler management system consisted of a boiler and a feed system control panel

located in an underground control room. The boiler control panel provided instrumentation for monitoring and recording data from the boiler and boiler feed water system. Flame interlocks and boiler management were provided by a Honeywell Model BC 7000 microcomputer burner control system. The explosives dissolving and blending system control panel provided instrumentation for monitoring and recording data from the explosives mixing system. Interlocking and sequencing of the explosives solutions were provided by a Allen Bradley programmable logic controller (PLC). A process flow diagram of the equipment is shown in figure 1.

Once the boiler is fired with fuel oil and is brought up to sufficient operating temperatures, a specified quantity of explosives is dissolved into a quantity of solvent (toluene) in one of the explosives dissolving tanks. The explosives are dissolved by mixing and indirect heating with steam from the boiler (100°F). The explosives/solvent solution is mixed with the fuel oil in the explosives blending tank and continuously mixed by the air diaphragm pump. The fuel oil/solvent/explosives solution is then fed to the boiler to produce steam. A sufficient quantity of excess air is maintained to ensure complete combustion. After operations, acetone is flushed through the system to decontaminate the system.

FIELD DEMONSTRATION TEST

The field demonstration test was initiated at Hawthorne Army Ammunition Plant, Hawthorne, NV, in October 1990 using the pilot scale system previously described[4]. Weston, Inc. was the contractor for this demonstration. The objectives of the pilot scale test were to determine the destruction efficiency of the system, to characterize the gaseous effluent, to identify operational and safety problems, and to evaluate the potential for future use of the technology on full scale operations. Prior to the operation of the pilot system a Hazard Analyses was conducted by Hercules Incorporated, Allegany Ballistics Laboratory. In addition, a Safety Plan and a Site Plan/Safety Submission were prepared, reviewed, and approved by all safety organizations in the chain of command including the Department of Defense Explosives Safety Board.

A total of eighteen tests were scheduled. There were three test sequences based on the type of fuel processed: Test Sequence I - No. 2 fuel oil only, Test Sequence II - No. 2 fuel oil/solvent/TNT, and Test Sequence III - No. 2 fuel oil/solvent/Composition B. A matrix of explosives concentrations and excess air percentages were scheduled. Figure 2 contains a summary of the planned tests and sequences.

TEST RESULTS AND CONCLUSION

Due to the expiration of Weston's research and development contract with USATHAMA, only five of the scheduled tests were conducted. Since there was a time constraint, the tests were conducted out of order. Three tests were completed using fuel oil only (T1, T2 and T3). These were used to characterize the boiler combustion characteristics, particularly nitrous oxide emissions at excess air levels ranging from 20% to 30%. Only the test using the 1% TNT in toluene (T5) with 30% excess air was completed satisfactorily. The pilot scale system was decontaminated with acetone, and the remaining tests canceled due to the expiration of Weston's contract.

Although the tests were not completed as scheduled, the technology once again demonstrated the potential to be an effective method to recover energy from waste explosives. Dilute solutions of TNT (1%) were safely and effectively used to supplement No. 2 fuel oil in an industrial boiler. A destruction and removal efficiency of 99.99% was achieved while cofiring this dilute solution of TNT. The nitrous oxide emissions were characterized for the tests completed and, as expected, the nitrous oxide emissions increased significantly when cofiring the explosives supplemented fuel. Several design modifications were identified which will be implemented before continuation of the tests.

CURRENT EXPLOSIVES PROGRAM

After significant delays, the previously scheduled tests are scheduled to resume at Hawthorne Army Ammunition Plant in 1993. The original test matrix will be repeated with the new system modifications. Although the propagation testing established the upper limits of explosives content that could be safely utilized in this technology, the ability to meet the air quality standards will establish the maximum explosives concentration limits. In addition, since this process will likely fall under RCRA, the limits may be established by the ability to achieve a 99.99% destruction rate efficiency and an average carbon monoxide emission limit of 100 ppm over a 60 minute period (corrected to 7% oxygen). It is also very likely that the nitrous oxide emissions will be a key parameter in obtaining environmental permits for this technology. Once the emissions from scheduled tests have been quantified, several engineering designs will be evaluated to optimize the process and reduce the emission within regulatory limits.

CURRENT PROGPESS ON THE USE OF PROPELLANTS

TECHNICAL AND ECONOMIC ANALYSIS

The Tennessee Valley Authority (TVA) - National Fertilizer and Environmental Research Center began investigating the feasibility of using propellants as a supplemental fuel for industrial combustors in 1990 [7]. A series of laboratory tests were conducted to evaluate the physical and chemical characteristics, as well as the chemical compatibility, of nitrocellulose-solvent-fuel oil mixtures. Unfortunately, these test indicated that solvation and mixing with fuel oil was not technically feasible or cost-effective due to the low solubility of nitrocellulose. However, an economic analysis did indicate potential cost effectiveness of using propellant-fuel oil slurries as supplemental fuels.

A technical and economical study was completed by TVA on the use of propellant-fuel oil slurries as a supplemental fuel in September of 1991[8]. The propellants studied were nitrocellulose, nitroguanidine, and AA2 double-base propellant. A series of tests were conducted to determine the physical and chemical characteristics, as well as the chemical compatibility, of propellant No. 2 fuel slurries. The propellant-fuel oil mixtures were determined to be compatible and stable. In addition, it was found that wet-grinding of AA2 double base propellant with No. 2 fuel oil using an Ultra-Turrax grinder was sufficient to reduce the particle size to acceptable levels. This study concluded that a 10 percent by weight nitrocellulose-, nitroguanidine-, or AA2 propellant No. 2 fuel oil slurries as supplemental fuel was a cost-effective disposal option. The 10 percent by weight concentration of propellant in the slurry was based on the viscosity that could be handled by a conventional, unmodified burner. Larger quantities could be disposed of, if burners could be retrofitted to handle fuels with higher viscosities.

PROPAGATION TESTING

Zero gap propagation of detonation tests were conducted to determine the sensitivity of propellant-No. 2 fuel oil slurries to detonation of a shock wave[9]. Two operational modes were evaluated: the dynamic or pumping mode, and the static or settled slurry mode. Supplemented fuels containing 10 percent by weight nitrocellulose, 15 percent by weight nitroguanidine, and 20 percent by weight AA2 double base propellants slurried in No. 2 fuel oil did not propagate a detonation in either operational modes.

CURRENT PROGRAM

The results of the laboratory and bench-scale studies have indicated the technical and economical feasibility of utilizing propellants as a supplemental fuel. The U.S. Army Toxic and Hazardous Materials Agency is currently negotiating a Memorandum of Agreement with the Naval Surface Warfare Center - Indian Head, Maryland, to establish a joint Service program to continuing the development efforts of the propellant supplemental fuel program. After completion of the tests using explosives at Hawthorne Army Ammunition Plant, the pilot scale system will be moved to Indian Head, Maryland. A pilot-scale demonstration on the use of propellant-fuel oil slurries is planned for the future.

CONCLUSION

Although additional research and development is needed before full-scale application of this technology, significant advancements have been made in the development of this technology. The future implementation of this technology could prove to be a cost-effective disposal alternative to incineration and OB/OD which will not only benefit the DOD but commercial industry as well.

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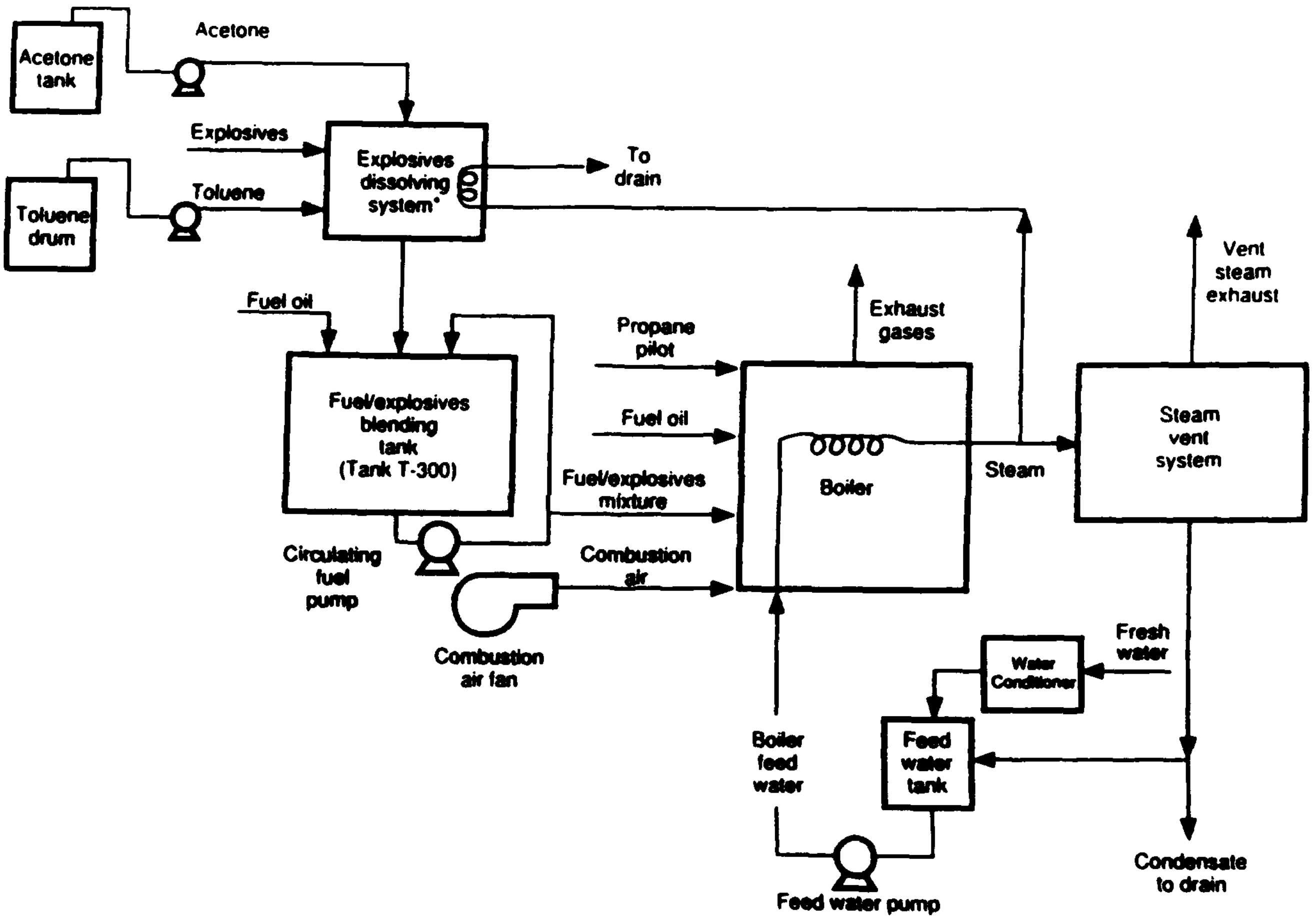

Figure 1
Process Flow Schematic

Test Sequence I
- Fuel oil feed
- Various excess air concentrations (20%, 25%, 30%)

% excess air	
20	T-1
25	T-2
30	T-3

Test Sequence II
- Fuel oil/solvent/TNT feed
- Various excess air concentrations

% excess air \ Weight % explosives in feed	1	10	15
20	T-10	T-7	T-9
25	T-12	(T-18)* T-11	T-8
30	T-5	T-6	T-4

Test Sequence III
- Fuel oil/solvent/Comp B feed
- Various excess air concentrations

% excess air \ Weight % explosives in feed	1	4	8
20	T-16		T-14
25		T-17	
30	T-13		T-15

*T-18 was a repeatability test.

Figure 2
Planned Test Sequences

Carbon Dioxide Blast/Vacuum Demilitarization

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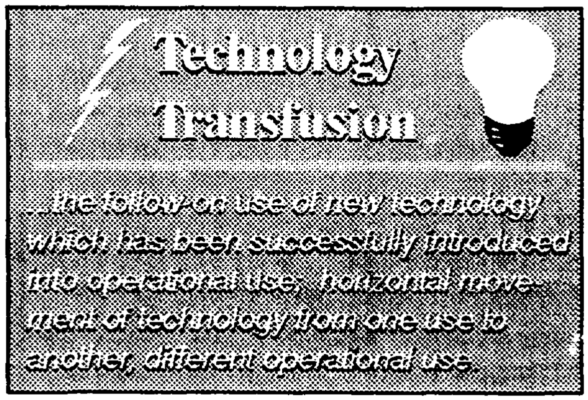
CRANE ARMY AMMUNITION ACTIVITY

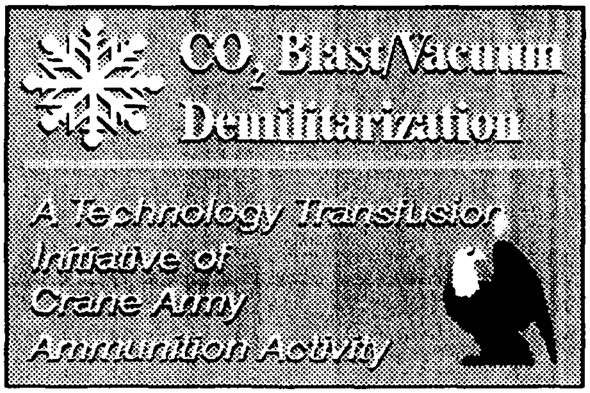
ABSTRACT: Carbon Dioxide Blast/Vacuum Demilitarization is an initiative intended to provide a new alternative to open-burning and open-detonation as a means of disposing of unwanted munitions. This initiative uses a commercially available Carbon Dioxide Blast Cleaning System which has been successfully adapted for use as a Demilitarization System by Crane Army Ammunition Activity, Crane Indiana. It is the first known use of CO_2 Blast Cleaning for demilitarization of live explosives. This initiative shows exceptional promise for reducing environmental risk while providing a cost effective disposal mechanism.

BACKGROUND: Many systems and products that have been in use for years are presenting ammunition managers with serious environmental problems when the time for disposal comes. Military ammunition and explosives comprise one of the more hazardous disposal problems in the Department of Defense.



Historically, planning for disposal of these items has been inadequate. They are consumables; they are gone once you've used them, so the alternatives to open-burning and open-detonation did not get the attention they do today. Over the past 30 years, only a handful of options for disposal of unused ammunition have been developed. The most widely used alternatives are incineration, steamout and high-pressure water washout. These methods do not come close to solving all of our disposal problems.

Now that we are really getting serious about environmental problems, the military is really getting serious about environmentally sound disposal methods. Some of these methods are being developed as brand new technology, others are resulting from adaptations of existing technology, which is known as Technology Transfusion.



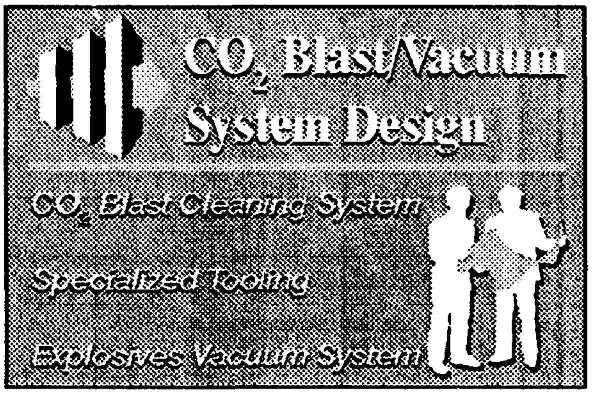
CONCEPT OVERVIEW: This concept mates a powerful vacuum with a CO_2 Blasting System, which is a sandblaster that uses dry ice pellets instead of sand. The blasting action of a CO_2 system turns the explosive filler of a projectile into powder, which can be collected in the vacuum. The pellet blaster and vacuum are mated together with special tooling that forms a closed system with a projectile. A working CO_2 Blast/Vacuum system has been successfully tested on explosive loaded projectiles. Work is underway on design enhancements to improve production efficiency.

The CO_2 Blast/Vacuum method offers substantial advantages over existing demilitarization methods. It is much simpler and requires less manpower than other systems. It doesn't require the costly water treatment plants that water based technologies do. The energy requirements are very low. The metal case can be reloaded with a new filler or turned-in for scrap without any additional cleaning. No other waste products are created, so the disposal problem is limited to the explosive itself, which in some cases can probably be sold. It may turn out to be the first economical alternative to disposal by detonation for some kinds of munitions.

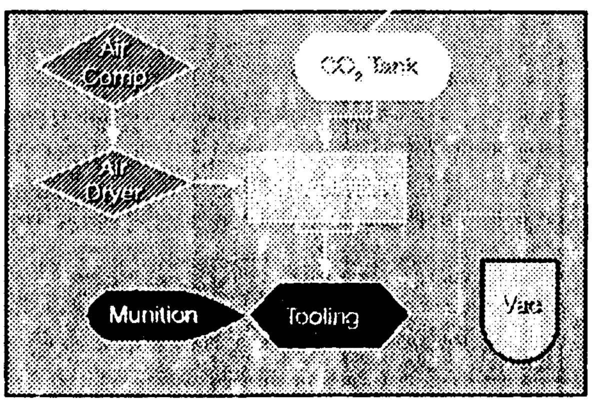
This initiative is still in the development phase, but only needs a few refinements to make it ready for a major production run. We have run a preliminary test of such a system on both inert materials and Explosive D. The prototype test used Navy 5"/54 projectiles. Inert items were used to ensure the system worked properly, then we tried it on Explosive D filled projectiles. Future testing of CO_2 Blast/Vacuum Demilitarization will be expanded to include other projectiles and explosives.

Hazards do exist. CO_2 blasting can produce powerful charges of static electricity. We control static charges by grounding the system throughout, and we included a built-in safety link that shuts the blaster off if electrical continuity is lost. In addition, we tested the system for static charges while the equipment was removing an inert filler. Our grounding system has proved adequate so far, but we will continue to watch closely for any indication of a static hazard.

CAAA is now in the process of analyzing the initial test data and redesigning the tooling for better efficiency. When that effort is completed, we'll be able to do more kinds of demilitarization, with greatly reduced hazardous waste and cost.



SYSTEM COMPONENTS: The demilitarization system we are using consists of a carbon dioxide blast cleaning system, ammunition tooling and an explosion-proof vacuum system. The CO_2 blast cleaning system components are the CO_2 pelletizer unit, an air compressor, an air dryer, and a liquid carbon dioxide storage tank. Specialized tooling mates the vacuum and the munition (a 5"/54 projectile for the test) to two kinds of explosive removal devices: a contour drill and the CO_2 blasting gun. The system uses a two-step process to remove the explosive from the projectile. The projectile is core-drilled with the contour drill first, then the CO_2 blasting system cleans out the rest of the explosive.



SYSTEM OPERATION: The projectile is placed in a lathe-type contour drill for processing. The drill uses a hollow shaft cutting bit that bores into the explosive filler as the projectile turns. The vacuum withdraws the powdered filler up the drill shaft as the bit cuts. A cam system causes the bit to follow the contour of the projectile cavity. Once the projectile has been core-drilled, the drill is retracted and positioned out of the way. A lining of explosive filler about 1/8 inch thick remains inside the projectile. The CO_2 blasting gun is mounted on the same positioning mechanism as the drill, and moves into position as the drill swings away. A brass bushing seals the connection between the blast gun and the vacuum. The CO_2 blast gun enters the projectile much like the drill bit does, but it doesn't require a cam system. The blasting action of the CO_2 pellets turns the explosive into powder, which is pulled out of the projectile by the vacuum. A special fitting allows the vacuum and the CO_2 blaster to work together, and a selector valve ensures the drill bit and the blast gun are not connected to the vacuum at the same time. When the projectile has been cleaned out, it is removed from the lathe chuck and the next one is put in its place. The first few projectiles processed on this system underwent extensive testing to determine the degree of cleanliness achieved, but the ultimate goal is a simple visual inspection to verify removal of the explosives.

HOW CO_2 BLASTING WORKS: The pelletizer creates CO_2 pellets by introducing liquid CO_2 into a low pressure chamber which causes the

liquid to turn into "snow". This CO_2 snow is extruded through a die to form the pellets. The pellets pass through an airlock where they enter the transport hose, and 35 psi pressurized air pushes them down the hose to the blasting gun. The blasting gun is supplied with high pressure blasting air through a separate hose. The blasting gun injects the CO_2 pellets into the high pressure airstream through a venturi at the opening of the nozzle. The nozzle accelerates the pellets up to supersonic speeds.

CONCEPT ORIGINATION: The concept for a CO_2 Blast/Vacuum system was formed by combining Air Force cleaning methods for bomb fuze wells and jet engines. The Air Force uses a blast/vacuum system to clean bomb fuze wells with glass bead blasting medium. Tinker Air Force Base uses a CO_2 blasting system to clean jet engine components. The Tinker system was featured in a "TechTIP" Technology Transfer Information Profile published by the Joint Technology Applications Office at Wright-Patterson Air Force Base.

We called the Process Engineering Section at Tinker AFB for information about CO_2 pellet blasting systems. Based on their advice, we contacted a company called Alpheus Cleaning Technologies, which is located in Rancho Cucamonga, California. Alpheus does sample testing for specific customer needs at either the customer's location or at their own facility in California. Since they agreed to do sample testing at their own location free of charge, we arranged a visit to try the concept with inert materials. The "proof of concept" test took place in the Alpheus test booth on November 8, 1990 and used an Alpheus CO_2 blasting machine.

TEST PREPARATIONS: Prior to visiting Alpheus, we prepared inert test samples and made a special test fixture to form a sealed system with a projectile, while mating the blast nozzle to the vacuum. We also coördinated with McAlester Army Ammunition Plant to give them an opportunity to participate in the test. The test articles were two 76mm projectiles press-loaded with a barium sulfate/magnesium sulfate mixture, two 76mm projectiles cast-loaded with "Filler E" (a mixture of wood rosin, stearic acid and dead-burned gypsum), and a 5-inch beaker (a plastic container that fits inside a 5-inch projectile) filled with an inert representative of Plastic Bonded Explosive (PBX). The McAlester Army Ammunition Plant representative brought two coffee cans filled with a slightly different kind of inert PBX.

TEST RESULTS: We tried the system on a press-loaded projectile first. We started working at 50 psi, which is the lowest blasting pressure possible, and found that very adequate for granulating the filler. The vacuum worked well, but the mating fixture severely limited the cleaning angles we could blast with. We started and stopped several times to allow inspection and tighten leaking seals on the fixture. Final cleaning had to be done without the vacuum fixture because of the limited cleaning angles. Total cleaning time was ten minutes. Next, we tried a projectile loaded with

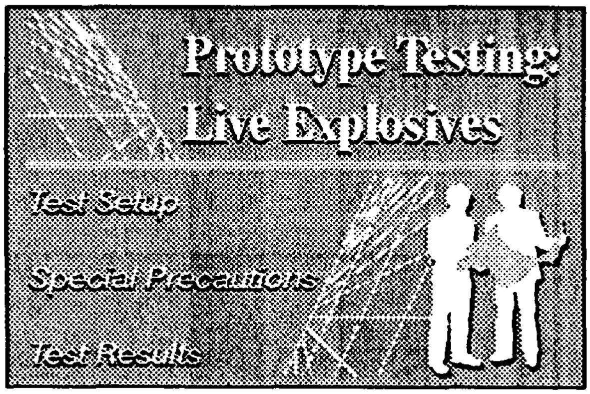
filler E. Again, we started at 50 psi blasting pressure. The filler E was much harder to grind up. Even after increasing the blasting pressure to 130 psi we only succeeded in creating a cone-shaped depression. We attempted to continue the test by removing the projectile from the fixture, but so much dust was created by blasting without the vacuum that we were forced to stop. However, cleaning was improved by the better angles achieved outside of the fixture. We put the second cast-loaded projectile in the fixture and concentrated the blast nozzle alongside the interior wall of the projectile. We were able to remove the filler E, but at a much slower rate than the pressed filler. The cavity paint was removed along with the filler.

Once we were finished with the projectiles we began testing the PBX samples. We anticipated that PBX would be very tough going for the CO_2 blasting system, so we chilled the beaker and one of the coffee cans in dry ice to make the samples more brittle. As we thought, the PBX samples were too resilient to break up very well with the CO_2 blaster. The best we found possible was one cubic inch of erosion in three minutes of blasting.

TEST SUMMARY: The test succeeded in showing that CO_2 blasting technology is definitely worth examination for use as a demilitarization method. The system we tested was able to clean out a pressed 76mm projectile in ten minutes at the lowest power setting. That would be faster than steamout (if you could steam out a pressed projectile), and slower than a drillout system. We were not satisfied with the test using filler E. The filler seemed much tougher than explosives such as Comp B or H-6 would be. After the CO_2 test was done we came across a test report on a water-jet system that also said filler E had different properties than actual explosives, and recommended adding 60 percent sand to replicate Comp B. We would like to try another test on filler E containing sand. We found the fact that the cavity paint was removed along with the filler an encouraging indicator of the system's cleaning power. If we can get the munitions that clean, we won't need to flash them (burn out explosives residue).

Our first design for a mating fixture proved that a vacuum could be used with a CO_2 blaster, but it also limited the cleaning effectiveness of the system. An improved mating fixture had to be developed to achieve better cleaning before we began tests on live explosives. Also, we had a tremendous static charge in our test fixture. We used a clear plastic tube so we could see the blasting nozzle, a feature we had to delete from our explosive tests for better grounding.

The CO_2 system did not show much promise for use with Plastic Bonded Explosives, or at least not on the cast variety. It may work better on press loaded types of PBX, perhaps we could try it on certain kinds of PBX sometime in the future. In the meantime, there are plenty of possibilities for developing demilitarization systems with TNT and RDX based explosives and that's where our testing program is most likely to be concentrated.



EQUIPMENT INSTALLATION: The CO_2 Blast/Vacuum system was installed in building 2504, an approved explosive operating building. The building has the necessary electrical power, compressed air, explosives vacuums and protective cells to adequately support this system. Equipment contractors installed the CO_2 tank and piping. The pelletizer contractor also provided training on how to operate the CO_2 system. CAAA engineers and technicians designed, installed and connected the rest of the system components.

SPECIAL PRECAUTIONS: Since the pelletizer unit is not explosion-proof, special care was taken to ensure the installation isolates the pelletizer from any possible exposure to explosive dusts and vapors. Only the blasting nozzle or "gun" is actually present in the cell where blasting takes place. The gun is explosion-proof and is connected to the pelletizer by a long set of hoses. The vacuum system is located in a position that isolates it from the operating cell and from the pelletizer unit. All vacuum components were inspected and refurbished before the tests began. Pneumatic operating controls were used, which are inherently explosion-proof. A control room was set up in a protective cell, and the system was monitored with a video camera.

SYSTEM TESTING: All equipment components of the system were thoroughly checked for proper operation before testing the system as a system. Initial testing to verify system operation and prove out specialized tooling was done entirely on inert loaded rounds. Inert testing was also used to allow Safety, Fire Department, Industrial Hygiene and Quality Assurance personnel to evaluate the system before attempting to use it on live rounds.

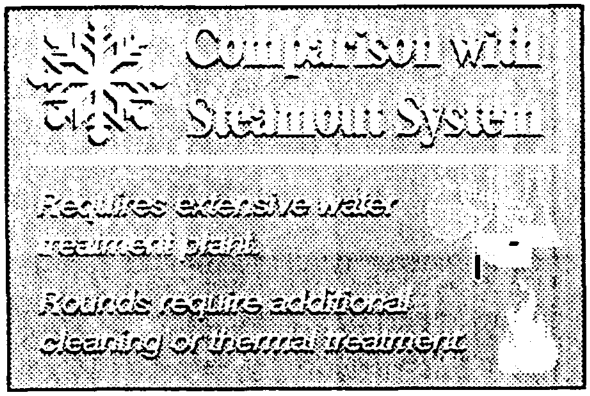
PRODUCTION TEST ITEMS: The CAAA testing program was designed to keep the process as simple and understandable as possible. We selected 5"/54 projectiles loaded with Explosive D as the lead test item. This ammunition has many attributes that made it especially suitable for our tests. It was available on station, we had tooling and equipment already designed for it, and empty bodies were available for use as inert test items. Explosive D is very insensitive to initiation from impact, and we have considerable experience demilitarizing Explosive D filled ammunition through the drill-out process. Using this ammunition allowed us to develop our tooling and procedures with very little risk of safety or engineering problems. The test period was limited to 16 rounds because of facility and funding constraints. Now that the test period is over, the test data is being used to develop criteria for certifying projectiles as "demilitarized"

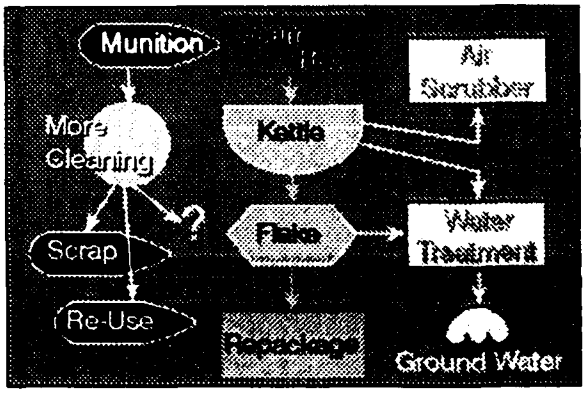
and free of any requirement for further cleaning. The test data will also be used to develop and refine Standing Operating Procedures and test authorizations for trying the system on other projectiles and explosives. Once we have more experience with the system, we will probably seek to try it next on Composition A-3, which is likely to be the most sensitive explosive we will use this process on. If we are successful with Composition A-3, we are confident that we would also be successful with a wide range of less sensitive explosives.

OPERATOR TRAINING: The purchase contract for the CO_2 pelletizer included four days of demonstration and training in its use. Those technicians who were the first to operate this equipment attended this training. We selected experienced equipment operators who are already qualified to run explosives drilling and vacuum machinery. The first operators also participated in the initial testing on inert loaded rounds. This gave them as much training as possible prior to the first use of the system on live rounds.

TEST PRECAUTIONS: An inert testing period preceded the first use of the system on live rounds. This allowed us to verify the equipment was working the way we wanted it to. The inert testing phase was also used as much as possible to familiarize safety, fire department and EOD personnel with the process.

When the system had been checked, tested and approved through inert testing, testing on live rounds began. Rounds were depalletized in a room separate from the operating cell. Only one round at a time was permitted in the operating cell. Both the drill-out and the CO_2 blasting steps were done remotely and monitored with a video system. After the first round was done, the equipment was shut down and we waited five minutes before entering the cell to ensure no hazard remained. The round was removed from the equipment and visually inspected. Some visible residue remained near the bottom of the projectile cavity, so the equipment was adjusted and the test was started again on another projectile. Again, some residue remained near the bottom of the round. The nozzle was removed and lengthened, and the system was tried again on additional rounds. This time residue was left near the top of the round. A new hydraulic cylinder with a longer stroke was installed to increase the length of travel of the CO_2 nozzle. We tried it again on several more rounds, and were able to remove all but a small trace of the explosive near the top. We feel confident that with a little more experience with the system we can make the adjustments necessary to get the projectiles completely clean.





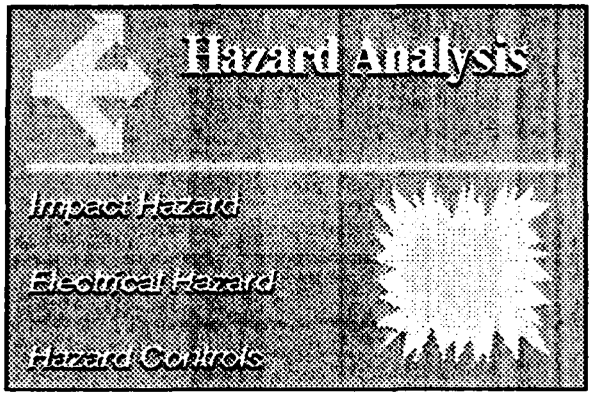
STEAMOUT SYSTEM CHARACTERISTICS: A Steamout Facility for demilitarization is much more complex than CO_2 Blast/Vacuum Demilitarization. The steamout facility at Crane has racks that hold the munitions at a downward angle while a steam probe is inserted into the case. As the explosive melts out, it drains through heated tracer lines to a collection kettle. The collection kettle keeps the explosive in a molten state until it is ready for further processing. Most of the water is drained off at this point and sent to the treatment plant. The kettle also requires a hood to capture the vapor rising from it, which uses a sophisticated air scrubber to remove the explosive contaminants.

The explosives collected in the kettle often require additional drying in a second kettle before it can be poured as pellets (much like bricks) or processed through a flaking machine. Once in a dry state, the explosive is packed in boxes.

The empty case is not clean enough to go directly from the steamout rack to the salvage yard. Cases being scrapped undergo thermal treatment, which means the remaining residue is burned out. If the cases are going to be reused, they have to cleaned out with a chemical solvent. Both of these alternatives generate additional waste streams.

LIMITATIONS OF STEAMOUT SYSTEMS: Steamout works well for cast explosives, such as TNT and TNT based compositions. However, it does not work for most press-loaded explosives, and does not work on many RDX based compositions. To be efficient, a steamout facility should operated 24 hours per day, because a lot of time can be lost in starting and stopping steamout production. And of course, a steamout plant requires an extensive boiler operation and a water treatment plant.

A CO_2 Blast/Vacuum Demilitarization system could be an excellent alternative to steamout. Procurement and installation costs are magnitudes less, and manpower requirements are much less too. A steamout facility is a permanent installation; a CO_2 system is relocatable, and can be moved from one place to another according to workload.



GENERAL INFORMATION: No one had ever tested or used a CO_2 Blast/Vacuum System as a demilitarization method before this test. Therefore, all potential hazards were evaluated and controlled prior to testing the system on explosives, and the system was tested on a relatively insensitive explosive.

Our hazard analysis concentrated on CO_2 blasting, as core drills and vacuums have been used with explosives for years, and the accompanying hazards and necessary safety precautions are well known. CO_2 blasting presents two hazards to explosive materials: shock from impact and static electricity. Friction, crushing, heat and chemical reaction hazards are not created by CO_2 blasting.

IMPACT HAZARD: CO_2 blasting accomplishes its work by bombarding the surface to be cleaned with dry ice pellets. These pellets hit the target surface at speeds from 700 to 1,500 feet per second, according to the equipment manufacturer. It is difficult to predict the hazard this impact might present to various kinds of explosives. Yes, we can calculate impact energy using pellet velocity, mass and surface area, but the energy threshold for reaction in a given explosive composition simply isn't available. The standard tests for impact sensitivity do not yield data that translate to usable numerical energy values. They are good for ranking the sensitivity of various compositions relative to each other, and for establishing the threshold for detonation, but little else. Ideally, we would like to know the threshold for reaction for any given explosive, and compare that with the energy produced by CO_2 pellet blasting. That simply isn't possible with the information available now. We **do** have information from fragment impact tests and high pressure water jet studies that suggested a reaction during CO_2 pellet blasting was highly unlikely, but we proceeded cautiously because of the lack of better data.

STATIC CHARGE HAZARD: CO_2 Blasting can build up a powerful static charge of electricity in ungrounded materials. We believe this is the single greatest hazard of CO_2 Blasting. The cold temperatures involved, and the extremely dry air we must use, are known to cause static charges unless effective controls are in place. During the initial test done in California, a charge of several thousand volts was measured in our tooling. However, the tooling was not grounded and a plastic component added to the problem. The production tooling is constructed entirely of conductive materials and is completely grounded. In addition, we have a built-in safety shut-off that shuts off the pelletizer if electrical continuity is

lost. The production equipment was also tested for static charges while in operation with inert materials. We found that a static charge was building on the projectile, so we added a grounded graphite brush that rubs on the rotating band, which solved the problem.

OTHER HAZARDS: Other possible hazards considered were dust escaping from the vacuum because of seals getting cold and shrinking; the vacuum not holding the pressure of CO_2 Blasting; and moisture condensing on the cold explosive when it is removed from the vacuum. None of these potential hazards materialized.

PROGRAM STATUS: Testing of the prototype CO_2 Blast/Vacuum Demilitarization system had to be terminated after running only 16 rounds, because the building had to be turned over for use with another project. The system will be removed and reinstalled in another location where a major production run can be done without conflicting with other workload. We are purchasing a new CO_2 storage tank and additional blasting equipment in anticipation of a renewed testing program in fiscal year 1993. (We used a leased storage tank for the test.) The report here represents program status as of 15 February, 1992.

CONCLUSION: Even though our CO_2 Blast/Vacuum initiative represents a tremendous advance in demilitarization capabilities, it does not solve all of the problems we face in this area. While it shows that technology transfusion is an extremely valuable tool, it also shows that we can't rely on the advance of technology to substitute for good, sound life cycle planning. We must do a better job of planning how to handle the disposal of ammunition and related products.

The requirement address disposal as a design element for new munitions has been in effect for several years now, but even so, viable alternatives to open burning and open detonation have not gotten the attention they deserve. A good way to get better, more cost effective disposal options would be to send the design to organizations that actually demilitarize munitions on a regular basis, and have them draw up the disposal plan. The DOD's most experienced "hands-on" experts, at Crane Army Ammunition Activity and McAlester Army Ammunition Plant, remain a hidden, untapped resource.

The CO2 Blast/Vacuum Demilitarization initiative shows they have the talent to develop innovative solutions to some of our toughest problems. Call (812) 854-1336, or DSN: 482-1336, for more information about government owned and operated demilitarization facilities.

CANADIAN AMMUNITION STORAGE MAGAZINES

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DEPARTMENT OF NATIONAL DEFENCE
CANADA

AUGUST 1992

CANADIAN AMMUNITION STORAGE MAGAZINES

BY

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A B S T R A C T

Canada's ammunition storage magazines, designed by the departmental engineers, can rightfully qualify for the title " The World's largest igloos " given their unprecedented characteristics in terms of structural engineering features (reinforced concrete box structure with a clear span of 17m, depth 28m and clear height of 5.7m) and storage capacity of 250,000 kg. of equivalent TNT of Hazard class/div 1.1. This paper describes the design criteria, design methodology, construction, cost and various requirements of safety, security, operation etc. employed in these magazines. Currently, 17 igloos have already been constructed and 11 others with reduced capacity but similar structural engineering features are being planned for construction in the summer of 1992. The siting of the battery of igloos is such that the static design required for the normal environmental loads is adequate to carry the large dynamic blast loads from accidental explosions without the undue premium usually paid to achieve blast resistant facilities. Special attention is drawn to the design controlled by the blast loads on the roof, and not on the head wall as seen in many short span igloos.

1. INTRODUCTION

The Canadian Forces Ammunition Depots are located across Canada in the varying climates of the country. Many of the ammunition storage facilities in these depots date back to the days of the second world war. Ammunitions are stored in various ways i.e. out in the open (Fig. 1) or inside of magazines of different forms of construction such as wood, steel Quonset huts, concrete block wall, precast panel wall etc.(Fig. 2). It has been determined that most of these magazines are deficient in many respects and do not meet the modern day requirements of safety, security, shelter, operation and long term warehousing.

Some deficiencies of the existing facilities are as follows:

a. The layout, with interior columns and/or load bearing walls, is awkward and inefficient in terms of operation and storage.

b. Low ceilings prevent the use of modern handling equipments and inhibit proper management of palletized stacks.

c. Untraversed magazines pose considerable threat to the surroundings in case of accidental explosions.

d. Traversed magazines have insufficient earth cover i.e. 0.15m on the roof which cannot carry any additional loads.

e. Insufficient ventilation in the magazines results in damp musty air conditions within the buildings.

f. Evidence of decay and rot in wooden magazines.

g. Temperature extremes within the steel Quonset magazines limit the life span of stored ammunitions.

h. Wood-core doors provide inadequate security and protection against accidental blast effects.

2. DEVELOPMENT OF STANDARD MAGAZINE

Hence, the Canadian Forces has embarked on a magazine replacement program with the development of a standard magazine to accommodate the long term warehousing requirements, maximize storage efficiency and improve safety and operations. Though the

inventory of ammunitions range from Hazard Division (HD) 1.1 to 1.4, the standard magazine is developed to house a Net Explosive Quantity (NEQ) of 250,000 Kg of equivalent TNT of HD 1.1. While this may result in some over design, this provides flexibility to the depot's operations without dedicating specific magazines to specific hazard divisions, given that the amount and nature of warehousing may vary throughout the year.

Figs. 3 & 4 show a schematic layout and details of the standard magazine based on 215 Kg of NEQ /cu.m of stack volume. The design also allows for a clear and column free operational aisle, fire inspection aisles and a wide sliding door. Thus, the " **World's largest igloo** " was launched into design to house an unprecedented NEQ of 250,000 Kg. of HD 1.1 within a structure of an equally unprecedented proportions of 17m clear span, 28m deep and 5.7m high.

3. DESIGN CRITERIA

.1 Safety

a. The structure should resist all normal loads such as its own weight, earth, snow and live loads on roof and lateral earth pressures on walls.

b. An accidental explosion within one magazine i.e. the donor should not result in propagation of detonations in adjacent magazines i.e. the acceptors. The donor is not expected to survive the accidental explosion from within it. There is no explicit requirement to either save or limit the level of damage to the acceptor.

c. Blast, fragments and fire associated with an accidental explosion within a donor should not pose significant hazard to other inhabited structures and public traffic routes in the vicinity.

.2 Security

a. Stored materials should be protected from direct hits with small arms and damage from indigenous animals.

b. Unauthorized access to the stored materials should be prevented. An independant utility room adjacent to each magazine is provided inaddition to an intrusion alarm system.

.3 Shelter

a. Materials and their packaging should be protected from moisture induced degradation.

b. Materials should be sheltered from extremes of temperature fluctuations.

c. The structure should protect its contents from external fire, lightning strikes etc.

.4 Operation

a. Storage area should be maximized.

b. Operating aisle should allow for the use of 2-ton fork lift trucks.

c. Doors should be wide enough to accommodate the backing of ammunition loaded trailers into the structure.

d. Smooth transition from the apron exterior to the structure interior floor is essential.

e. Vertical clearance should provide for long term stacking height of 5 pallets.

4. DESIGN METHODOLOGY

.1 DESIGN FOR NORMAL LOADS (STATIC)

a. The structure is analyzed as a 2-dimensional portal frame for all normal loads such as dead weight, earth, snow and live load on roof and lateral earth pressure on walls (Fig.5).

b. The results of the frame analysis are modified to account for the two-way slab action of the roof slab. This is done by reducing all the values obtained from the roof in the 2-D analysis by a reduction factor. This factor is determined to be the average of the values obtained from frame analysis and the two-way slab analysis at both support and mid-span locations. Further refinements using 3-D finite element analysis of a box structure is not considered essential, given that the applied loads are generally uniform. Fig. 6 shows some representative values of member forces

obtained from this analysis.

c. According to the National Building Code of Canada (Ref.1), the building structure is designed using the limit states design for various load and load combination factors (Fig. 7).

d. The results of the normal load analysis clearly illustrate the optimum level of design achieved in the structure without excess capacity (Fig. 8).

.2 DESIGN FOR ACCIDENTAL BLAST LOADS (DYNAMIC)

SPACING OF IGLOOS AND CALCULATIONS OF BLAST LOADS

a. A literature survey of the igloos designed and constructed in the past (Refs. 2 & 4) indicates the following:

- span of igloos about half as that of the Canadian igloo.
- design NEQs smaller than that of the Canadian NEQ.
- no consistency in the evaluation of blast loads.
- igloos spaced at the so called " Standard Scaled Distances ".

b. Given the immense structural dimensions and the NEQ of the Canadian igloo, the application or extrapolation of existing data in the design process raised some concerns. Consequently, assistance was sought from the late Dr. Wilfred Baker of U.S., an eminent authority on blast physics, in determining the design blast loads for the Canadian igloo.

c. After studying references 5, 6 & 7, Dr. Baker concluded that the results obtained from model igloos listed in Ref. 5 could be used for the Canadian design. Based on Ref. 5, Pressure-Distance and Scaled Impulse-Distance diagrams were constructed by Dr.Baker (Fig. 9 & 10). Figs. 11 & 12 show comparisons between the design curves recommended by Dr.Baker and those obtained from a more recent study (Ref.8). While some similarities exist, differences are also noted between the two methods giving rise to the continuing concern about the accuracy of the prediction of air blast loads from igloos.

d. In laying out the igloos, various positions for

the front to back and side to side siting were attempted before arriving at the final front-back distance of 90m and side-side distance of 35m (Figs. 13 & 14).

e. The Canadian igloos are located at scaled distances (m/Kg^.33) of front to back 1.43 (Standard 0.8) and side to side 0.56 (Standard 0.5). The siting distances are controlled by the magnitude of blast loads on the long span roof and not by the reflected pressures on the front wall/door, as noted in many short span igloos. Fig. 15 lists the various pressure-impulse combinations acting on the elements of an acceptor assuming that any igloo can become a potential explosion site within the battery of igloos.

DYNAMIC DESIGN OF ELEMENTS

a. Each element is considered as a separate component i.e. roof as a two-way slab component, side and rear walls as one-way vertical components, front wall as a two-way component and door as a one-way horizontal component between the pilasters. The roof also acts as a horizontal diaphragm between the end walls transferring the lateral blast loads to the foundation through shear wall action.

b. Calculations of dynamic properties and the response of the elements using single degree of freedom analysis are performed in accordance with Ref.3 with appropriate adjustments made to accommodate the Canadian Codes. For reinforced concrete, Type II sections as in Ref.3 are employed.

c. Fig.16 shows the resistance-deflection characteristics of the roof slab based on three different end conditions. In the case of wall continuity, the ultimate support moment for the roof slab is restricted to that provided by the wall at the roof-wall junctions. Fig.17 indicates the idealized equivalent resistance diagram which is determined after making allowance for the dead load and weight of earth that act continuosly on the roof. Fig.18 shows an alternative method of calculation by reducing the ultimate resistance by the amount of dead load and weight of earth. In this case, the available resistance diagram is as shown in the figure. Fig.19 summarizes the results obtained by both methods and shows little difference in this instance. The maximum dynamic displacement for the roof slab is about 400mm and is included in the vertical clearance. A similar

resistance-deflection curve obtained for the one-way rear wall element is shown in Fig.20. Adjustments similar to the one for the roof dead load are made to this curve to account for the lateral earth pressure acting on the wall.

d. A summary of the dynamic response obtained for all the elements is shown in Fig.21. Again, it is noted that the dynamic design is also optimized without excessive reserve capacity.

e. Figs.22 & 23 show details of the igloo and the hanging sliding door including the locking mechanism.

CRATERING EFFECTS

Being a standard design, calculations are performed to determine the true crater dimensions in all types of ground conditions (Fig.24). These calculations indicate that the igloos are located well beyond the crater limits. In these calculations, the effect of the nominally reinforced 300mm thick floor slab has been ignored. If taken into account, this should further minimize the extent of true cratering.

UTILITY ROOM

This is not specifically designed to be blast resistant like the igloo. However, some mass is provided in the building with 400mm thick nominally reinforced walls and roof that are capable of resisting some nominal blast loads.

5. CONSTRUCTION FEATURES

a. The sequence of construction has varied from contractor to contractor depending on the number of igloos in the contract. In a recent contract involving sixteen igloos, the following sequence was found to be convenient:

- foundations for all walls were laid first.
- the rear wall and the side walls upto about 9m from the rear wall were poured upto the horizontal construction joint.
- the remaining side walls upto a meter from the front wall were poured upto the horizontal construction joint.
- the floor slab was cast in two stages i.e. the rear three-quarter portion first followed by the

remaining front portion except the entry ramp. Completion of floor slab before casting the front wall provides free access to the floor construction. This also prevents heat build up within the walls of the igloo during the summer months which affects the finishing operations on the floor.

- the front wall including the pilaster, the canopy and the remaining portions of the side walls were poured upto the construction joint (Fig.26)
- the roof slab was poured as one unit (Figs.25 & 29)
- the entry ramp and the front concrete sill were completed.
- retaining walls and the utility room were completed.
- the sliding door was hung from the runner beam under the canopy (Fig.28)
- finally, all waterproofing, insulation and earth traverse were placed sequentially (Fig.30)

b. It is very important that the roof slab is not allowed to act as a one-way slab during construction as the residual strength available to handle the construction loads will not be adequate. Consequently, the construction should allow for immediate shoring under the roof slab after the removal of the forms and that the shoring shall remain in place until the whole roof slab is cast to comply with the design requirements of a two-way slab slab action(Fig.27).

c. Fig.31 shows the concrete strengths obtained in the various magazines. They are consistently well above the design requirements. Due to the congestion of reinforcement in areas like the pilaster, superplasticizers were permitted in these localized areas. In spite of this, honeycombing occurred in some areas and had to be remedied.

d. Since the ends of the roof and walls are designed to be within 2 to 4 degrees rotations, double leg stirrups are placed in a staggered fashion throughout to ensure post-elastic behaviour.

e. The slope of the earth traverse on the sides and rear is 1:3, flatter than usual to facilitate maintenance. Besides, flatter slope improves the blast loading characteristics on the mounded igloo structure. The traverse is compacted to 95 percent proctor density while the earth covering over the roof is compacted to 80 percent.

f. An exterior lightning protection system on poles is provided over each igloo. In addition, all reinforcement in roof and walls, metal vantilators and door are electrically

bonded and grounded.

g. The igloo is also equipped with an intrusion alarm system, an automatic sprinkler system and a hot water radiant heating system.

h. A natural ventilation system with air intakes and chimney outlets is provided. All openings into and from the igloo are protected with security grills and insect screens.

6. COSTS

a. At the time of writing this paper, another contract is being tendered for the construction of 11 igloos with reduced capacity of 40,000 Kg. of NEQ /igloo but with similar structural dimensions (Figs.32 & 33). In this case, the scaled distances are front-back 1.02 and side-side 0.64.

b. However, many igloos have already been constructed. Fig.34 provides a summary of the total project cost including all ancillary costs. It is intersting to note that the cost per Kg. of NEQ stored reduces as the NEQ increases. The two earlier igloos shown in Fig.34 have cranes on gantry beams for interior operations.

7. CONCLUSIONS

a. An optimum design has been achieved for the Canadian igloo to withstand both normal and accidental blast loads. Very little premium in the form of special double leg stirrups is paid to achieve the blast resistant capabilites.

b. Intermagazine distances are greater than the so called standard spacings used for igloos. This is due to the design being controlled by blast loads on the large span roof instead of the loads on the front wall/door, as noted in many short span igloos.

c. The Canadian igloo provides for storage efficiency and ease of operation with column free interior, wide doors and locally depressed floor slab for smooth entry from the apron exterior to the structure interior.

d. The Canadian igloo can rightfully earn the title " **The World's Largest Igloo** " with its unprecedented structural dimensions and the immense NEQ capacity.

8. REFERENCES

1. National Building Code of Canada

2. Canadian Explosives Safety manual
   (C-09-153-001)

3. Structures to resist the effects of accidental explosions
   (ARLCD-SP-84001)

4. Manual on NATO Safety Principles for the storage of Ammunition and Explosives
   (AC258-D258)

5. Blast parameters from explosions in model earth covered magazines
   (BRL MR 2680)

6. ESKIMO - VI Model Tests
   (ARBRL-TR-02215)

7. ESKIMO - VI Test results
   (NCEL TR R889)

8. A re-examination of the airblast and debris produced by explosions inside earth-covered igloos
   (NAVSWC TR 91-102)

ACKNOWLEDGEMENTS

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AMMUNITION STORAGE LAYOUT

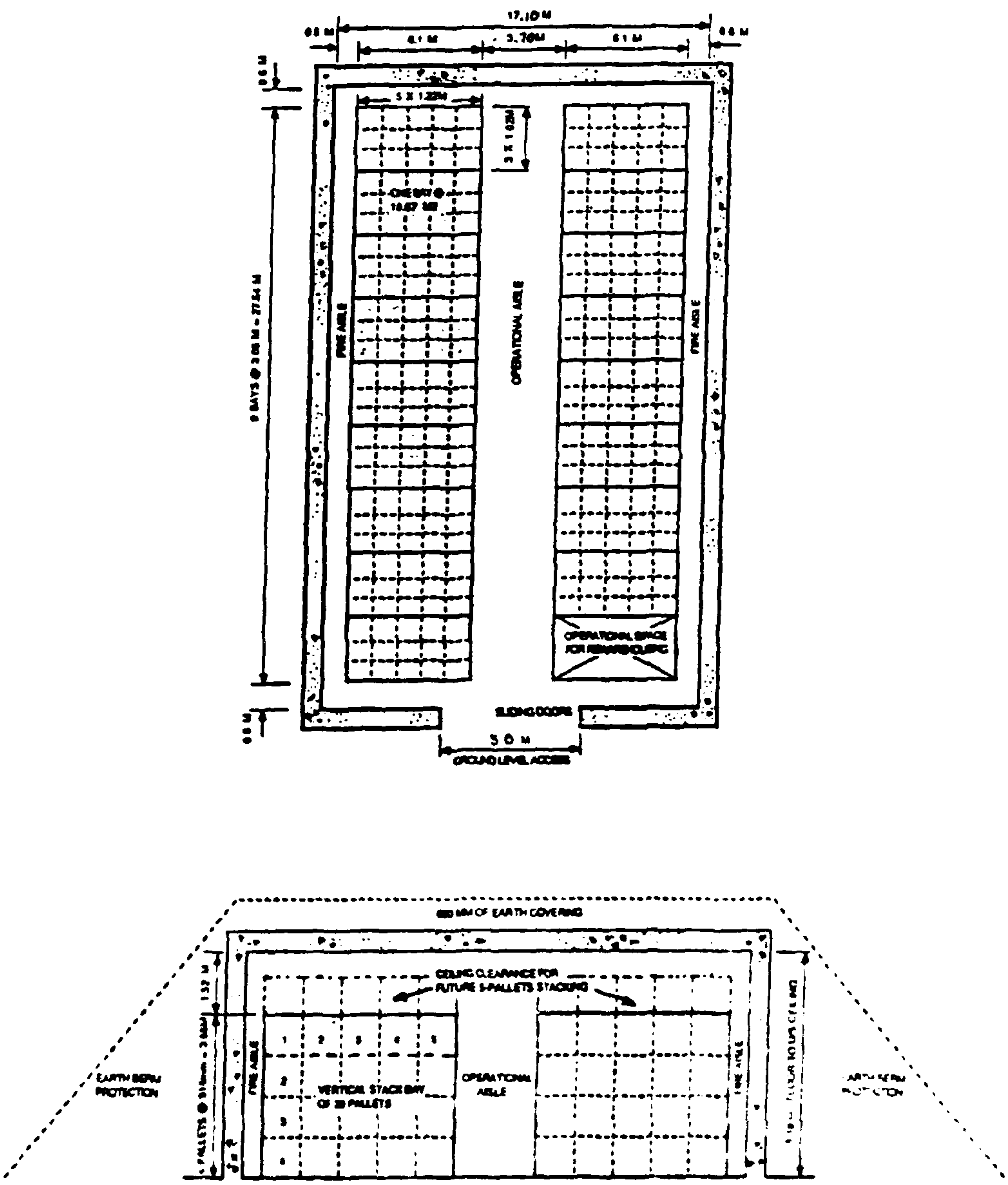


Fig.3 Schematic layout

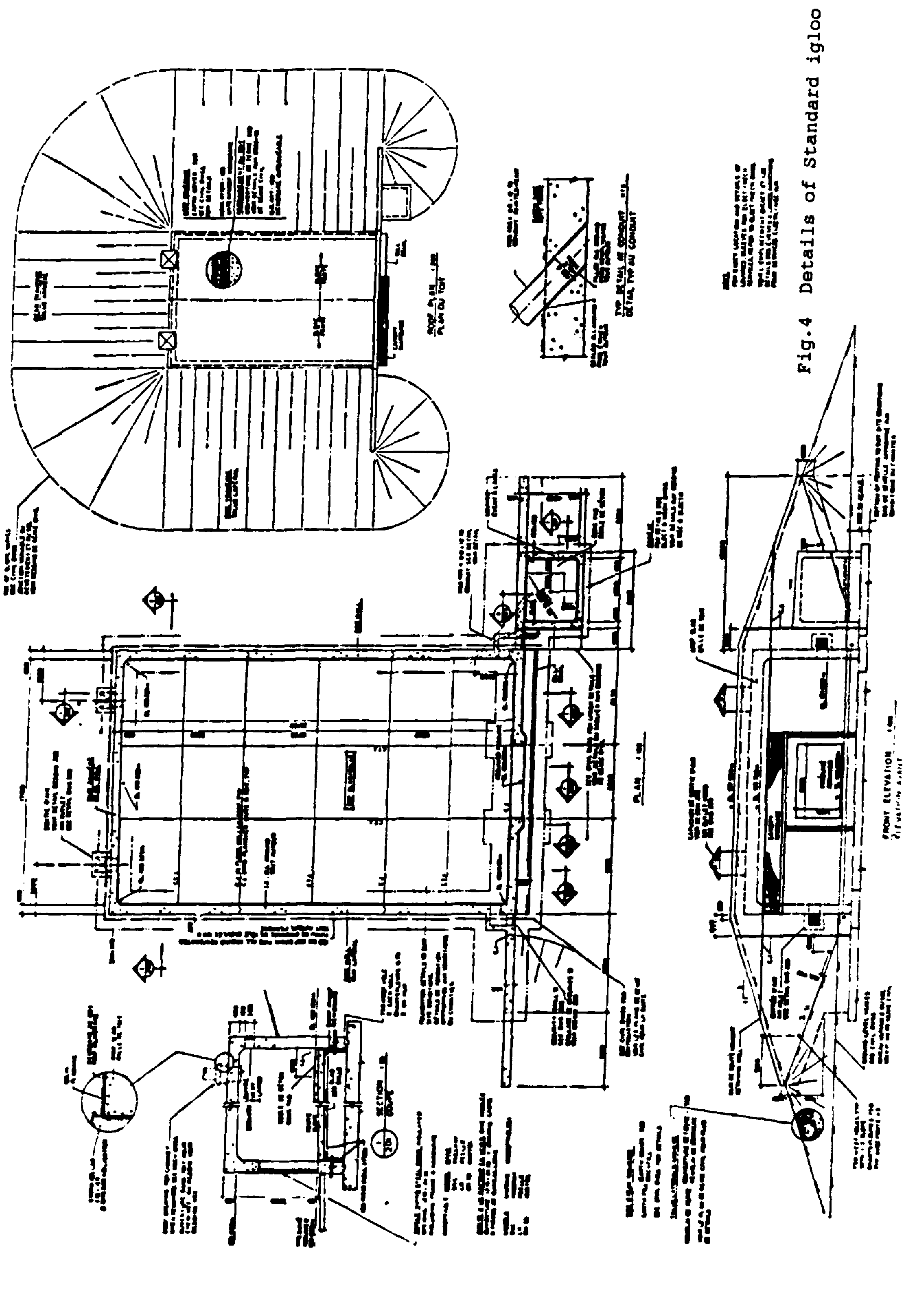


Fig.4 Details of Standard igloo

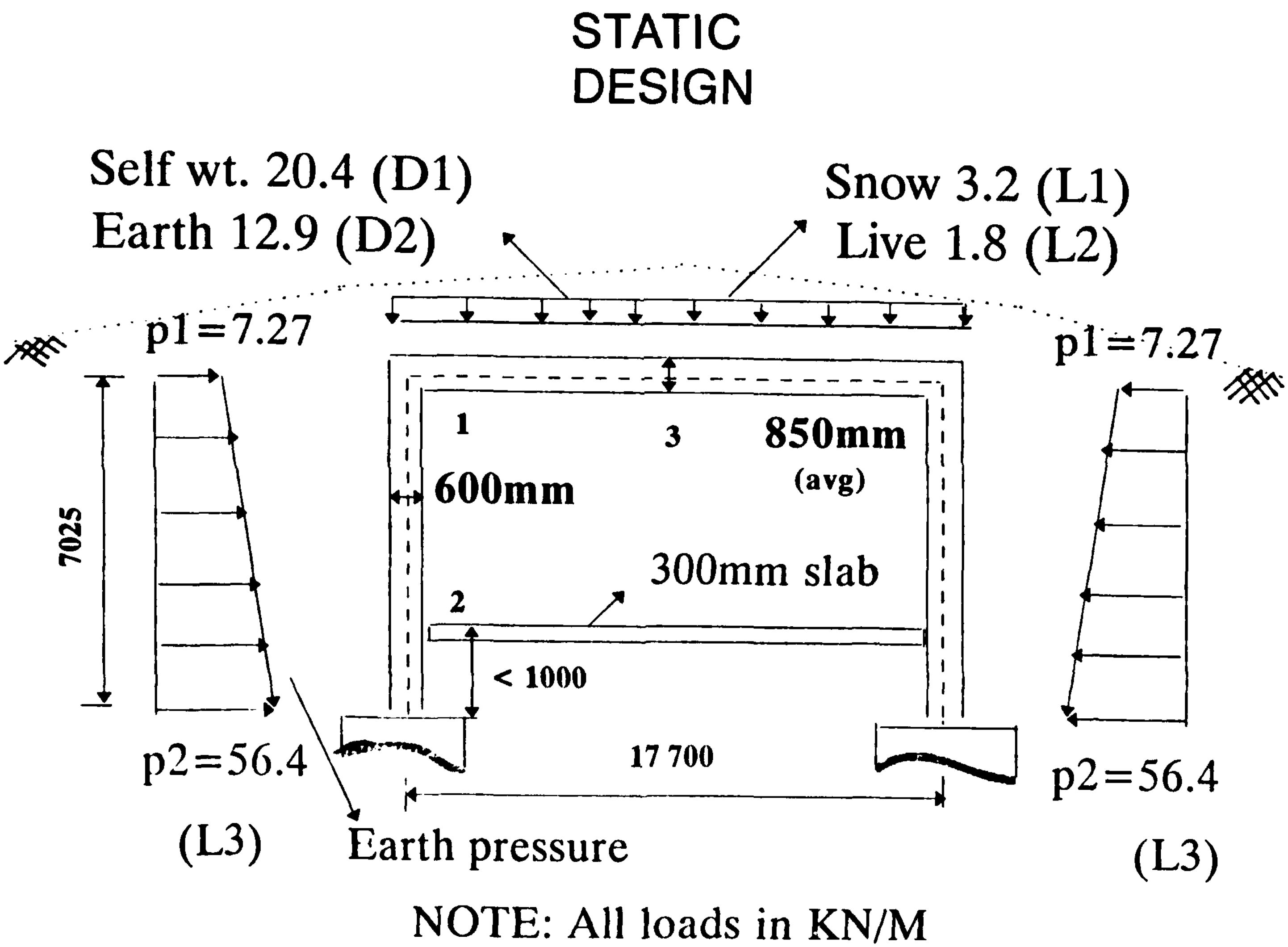

STATIC
DESIGN
Self wt. 20.4 (D1)
Earth 12.9 (D2)
Snow 3.2 (L1)
Live 1.8 (L2)
p1=7.27
p1=7.27
7025
1
3
850mm
(avg)
600mm
300mm slab
2
< 1000
17 700
p2=56.4
p2=56.4
(L3)
(L3)
Earth pressure
NOTE: All loads in KN/M

FIG.5

***** LOAD INITIALIZING DATA *****

load case	# loaded joints	# support settlemnts	# loaded members	describe load case
1	0	0	4	SELF WEIGHT
2	0	0	2	EARTH ON SIDE WALL (UDL)
3	0	0	2	EARTH ON SIDE WALL (TRIANGULAR)
4	0	0	2	EARTH ON ROOF
5	0	0	2	SNOW & L.L. ON ROOF (3.2 + 1.8)

Note: Load Case 1 specified as self-weight. Joint and Member load data for Load Case 1 is ignored. Self-weight is automatically calulated.

***** MEMBER FORCES *****

Load Case Results

mem no	load case	Joint no	x-axial kN	y-shear kN	z-shear kN	x-tors'n kN-m	y-moment kN-m	z-moment kN-m
1	1	1	176.779	0.000	-42.343	0.000	297.460	0.000
		2	-275.832	0.000	42.343	0.000	0.000	0.000
	2	1	0.000	0.000	-28.226	0.000	18.895	0.000
		2	0.000	0.000	-22.846	0.000	0.000	0.000
	3	1	0.000	0.000	-66.058	0.000	59.876	0.000
		2	0.000	0.000	-106.546	0.000	0.000	0.000
	4	1	114.165	0.000	-27.345	0.000	192.099	0.000
		2	-114.165	0.000	27.345	0.000	0.000	0.000
	5	1	44.250	0.000	-10.599	0.000	74.457	0.000
		2	-44.250	0.000	10.599	0.000	0.000	0.000
2	1	1	42.842	0.000	176.659	0.000	-297.460	0.000
		3	-42.343	0.000	.120	0.000	-483.731	0.000
	2	1	28.225	0.000	-.080	0.000	-18.895	0.000
		3	-28.225	0.000	.080	0.000	19.600	0.000
	3	1	66.058	0.000	-.187	0.000	-59.876	0.000
		3	-66.058	0.000	.187	0.000	61.528	0.000
	4	1	27.668	0.000	114.087	0.000	-192.099	0.000
		3	-27.668	0.000	.078	0.000	-312.393	0.000
	5	1	10.724	0.000	44.220	0.000	-74.457	0.000
		3	-10.724	0.000	.030	0.000	-121.083	0.000
3	1	3	42.343	0.000	.120	0.000	483.731	0.000
		4	-42.842	0.000	176.659	0.000	297.460	0.000
	2	3	28.225	0.000	.080	0.000	-19.600	0.000
		4	-28.225	0.000	-.080	0.000	18.895	0.000
	3	3	66.058	0.000	.187	0.000	-61.528	0.000
		4	-66.058	0.000	-.187	0.000	59.876	0.000
	4	3	27.668	0.000	.078	0.000	312.393	0.000
		4	-27.668	0.000	114.087	0.000	192.099	0.000
	5	3	10.724	0.000	.030	0.000	121.083	0.000
		4	-10.724	0.000	44.220	0.000	74.457	0.000

Linear Elastic analysis results Str No. 01

FIG.6

*** LOAD COMBINATION DATA ***

Load Comb	Load Case	Comb Fact	Load Case	Comb Fact	Load Case	Comb Fact	Load Case	Comb Fact	Load Case	Comb Fact	Load Case	Comb Fact
1	1	1.25	2	1.5	3	1.5	4	1.25				
2	1	1.25	2	1.5	3	1.5	4	1.25	5	1.5		

Load Combination Results

mem no	load Comb	Joint no	x-axial kN	y-shear kN	z-shear kN	x-tors'n kN-m	y-moment kN-m	z-moment kN-m
1	1	1	363.681	0.000	-228.536	0.000	730.106	0.000
		2	-487.496	0.000	-106.978	0.000	0.000	0.000
	2	1	430.056	0.000	-244.434	0.000	841.791	0.000
		2	-553.871	0.000	-91.080	0.000	0.000	0.000
	1	1	229.562	0.000	363.034	0.000	-730.106	0.000
		3	-228.938	0.000	.647	0.000	-873.462	0.000
	2	1	245.648	0.000	429.363	0.000	-841.791	0.000
		3	-245.024	0.000	.692	0.000	-1,055.086	0.000
3	1	3	228.938	0.000	.647	0.000	873.462	0.000
		4	-229.562	0.000	363.034	0.000	730.106	0.000
	2	3	245.024	0.000	.692	0.000	1,055.086	0.000
		4	-245.648	0.000	429.363	0.000	841.791	0.000
4	1	4	363.681	0.000	228.536	0.000	-730.106	0.000
		5	-487.496	0.000	106.978	0.000	0.000	0.000
	2	4	430.056	0.000	244.434	0.000	-841.791	0.000
		5	-553.871	0.000	91.080	0.000	0.000	0.000

Notes:
1. Positive axial forces act in the positive local (member) x direction.
2. Positive shear forces act in the positive local (member) y,z directions.
3. Pos. moments act in Pos. local x,y,z directions using Right Hand Rule.
4. Reduce above values from roof loadings by factor 0.9 to allow for two-way roof slab action.

Load Combination Results

jt no	load comb	X-displ mm	Y-displ mm	Z-displ mm	X-rot'n radians	Y-rot'n radians	Z-rot'n radians
1	1	.0391	0.0000	-.1811	0.00000	.00214	0.00000
	2	.0347	0.0000	-.2094	0.00000	.00266	0.00000
2	1	0.0000	0.0000	0.0000	0.00000	-.00026	0.00000
	2	0.0000	0.0000	0.0000	0.00000	-.00052	0.00000
3	1	0.0000	0.0000	-17.0699	0.00000	0.00000	0.00000
	2	0.0000	0.0000	-20.7923	0.00000	0.00000	0.00000
	1	-.0391	0.0000	-.1811	0.00000	-.00214	0.00000
	2	-.0347	0.0000	-.2094	0.00000	-.00266	0.00000
5	1	0.0000	0.0000	0.0000	0.00000	.00026	0.00000

Linear Elastic analysis results

Str No. 01

FIG.7

RESULTS

(STATIC DESIGN)

ELEMENT	FLEXURE + AXIAL		SHEAR	
	Actual Rft. (mm^2/m)	Required Rft. (mm^2/m)	Actual (mpa)	Allowable (mpa)
Walls (one-way)	2500	2300	0.56	0.99
Roof (two-way)	6000	6200	0.65	0.93

FIG.8

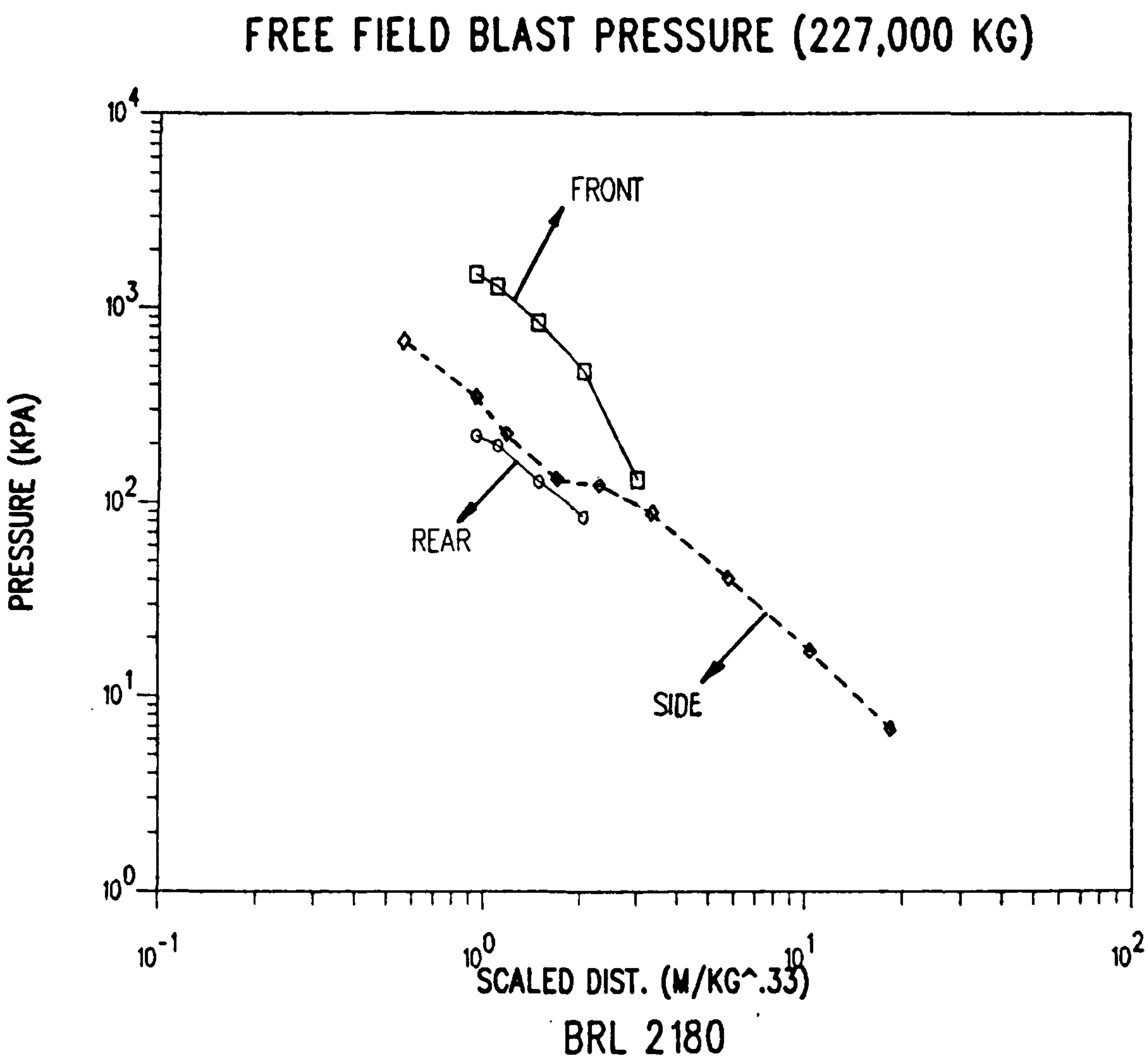
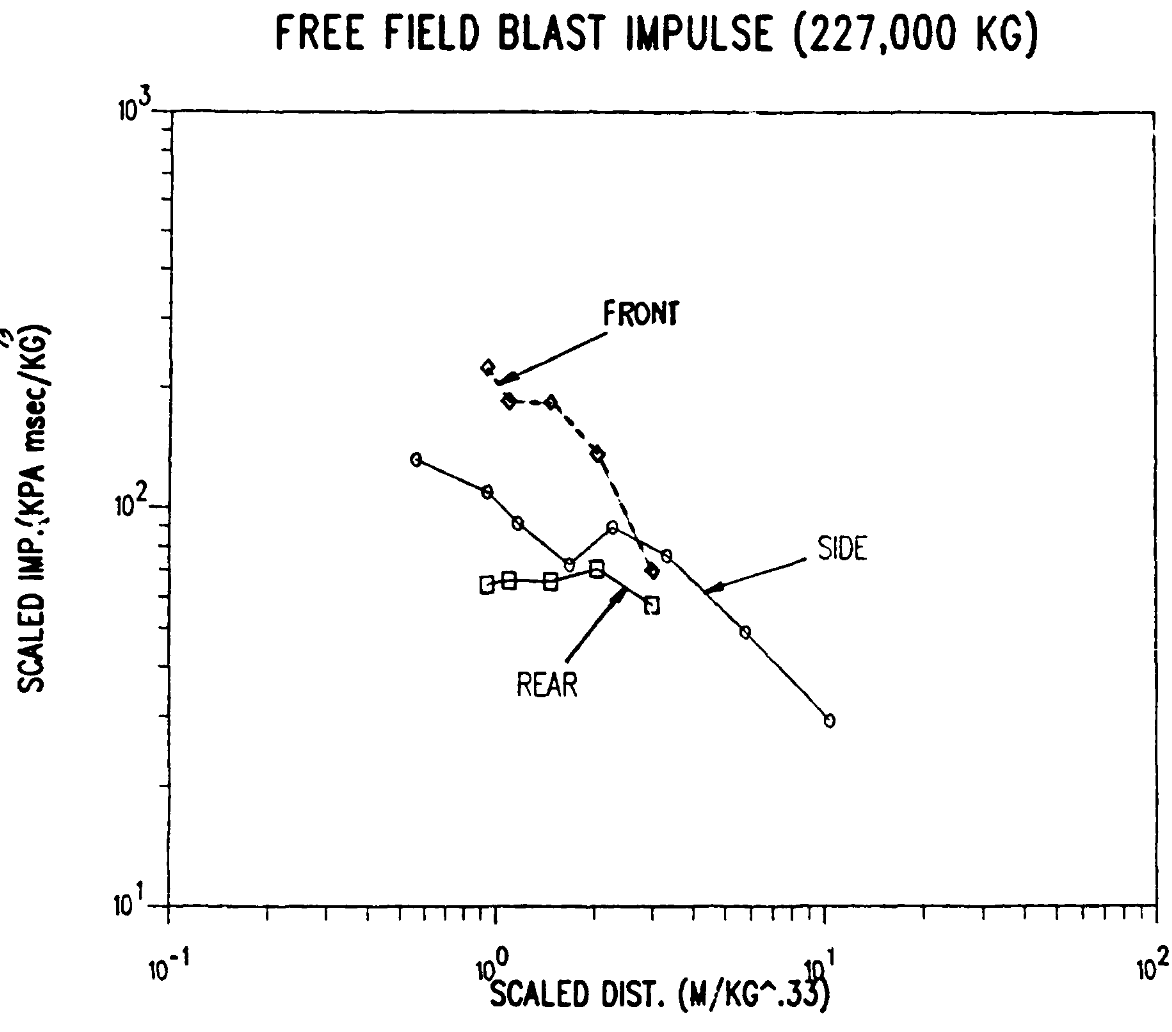
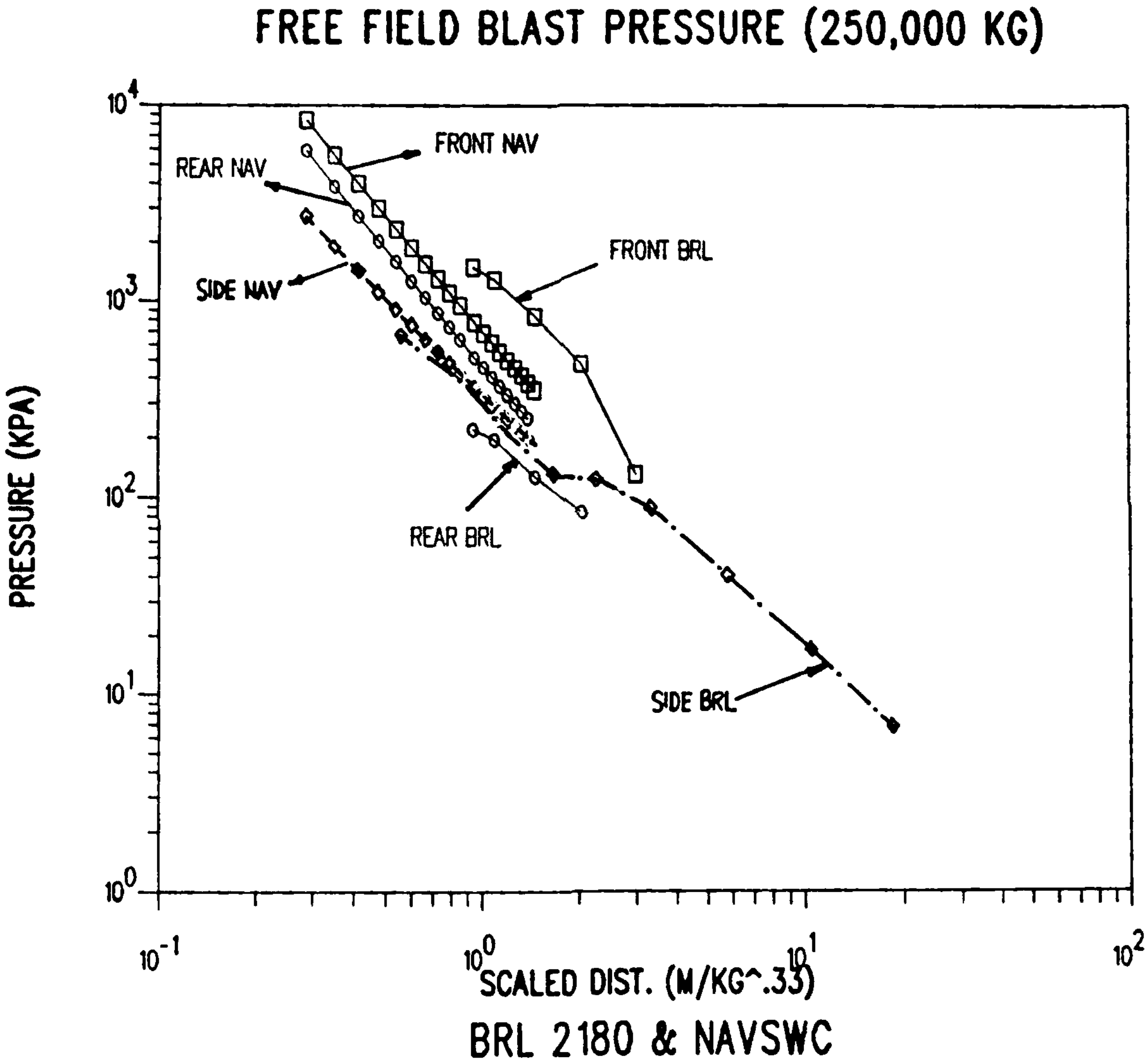

FREE FIELD BLAST PRESSURE (227,000 KG)
FRONT
REAR
SIDE
PRESSURE (KPA)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
SCALED DIST. (M/KG^.33)
BRL 2180

FIG.9



FREE FIELD BLAST IMPULSE (227,000 KG)
SCALED IMP. (KPA msec/KG)
SCALED DIST. (M/KG^.33)
BRL 2180
FRONT
SIDE
REAR

FIG.10



FREE FIELD BLAST PRESSURE (250,000 KG)
FRONT NAV
REAR NAV
FRONT BRL
SIDE NAV
REAR BRL
SIDE BRL
PRESSURE (KPA)
SCALED DIST. (M/KG^.33)
BRL 2180 & NAVSWC

FIG.11

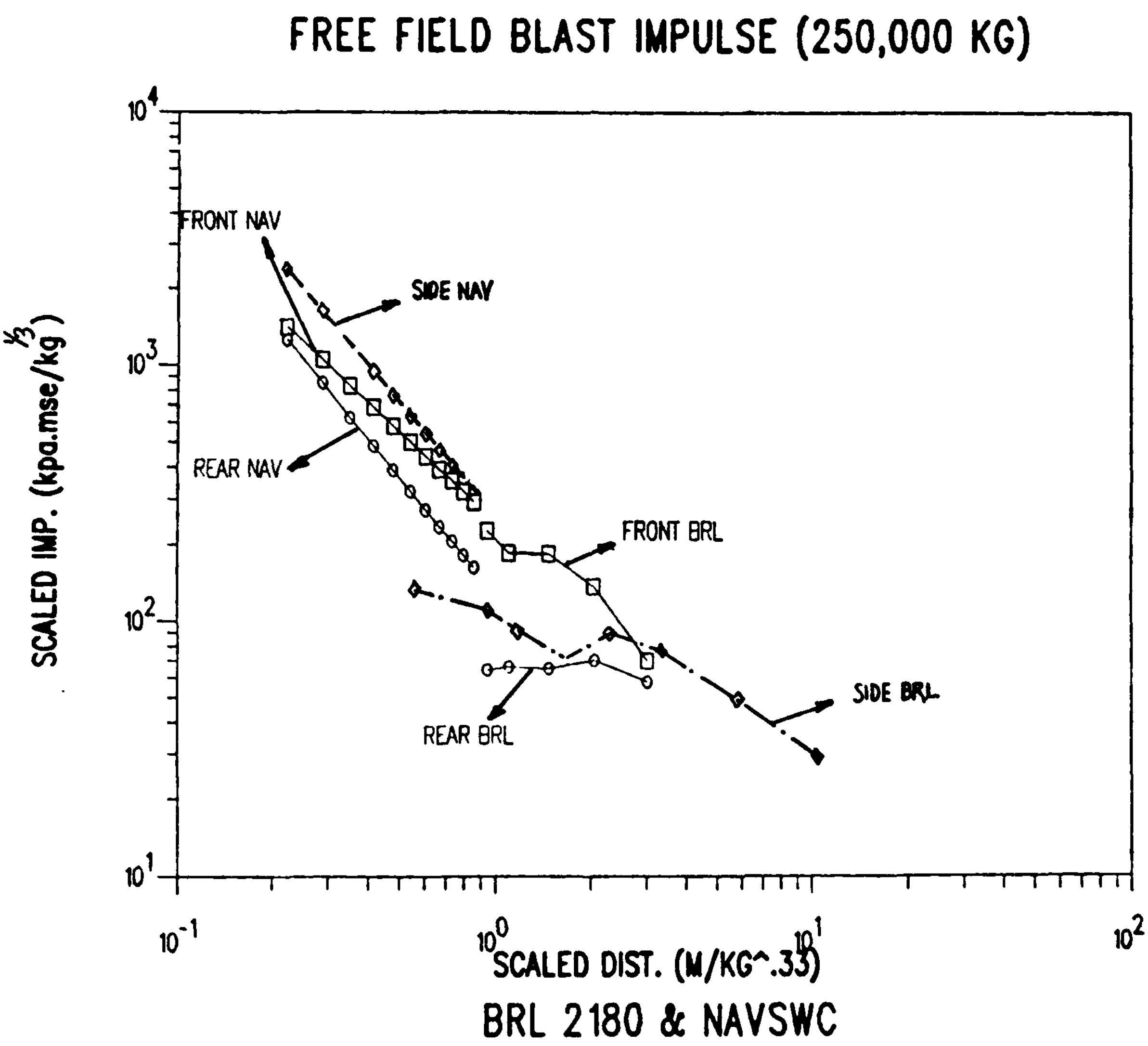

FREE FIELD BLAST IMPULSE (250,000 KG)
SCALED IMP. (kpa.mse/kg^1/3)
FRONT NAV
SIDE NAV
REAR NAV
FRONT BRL
SIDE BRL
REAR BRL
SCALED DIST. (M/KG^.33)
BRL 2180 & NAVSWC

FIG.12

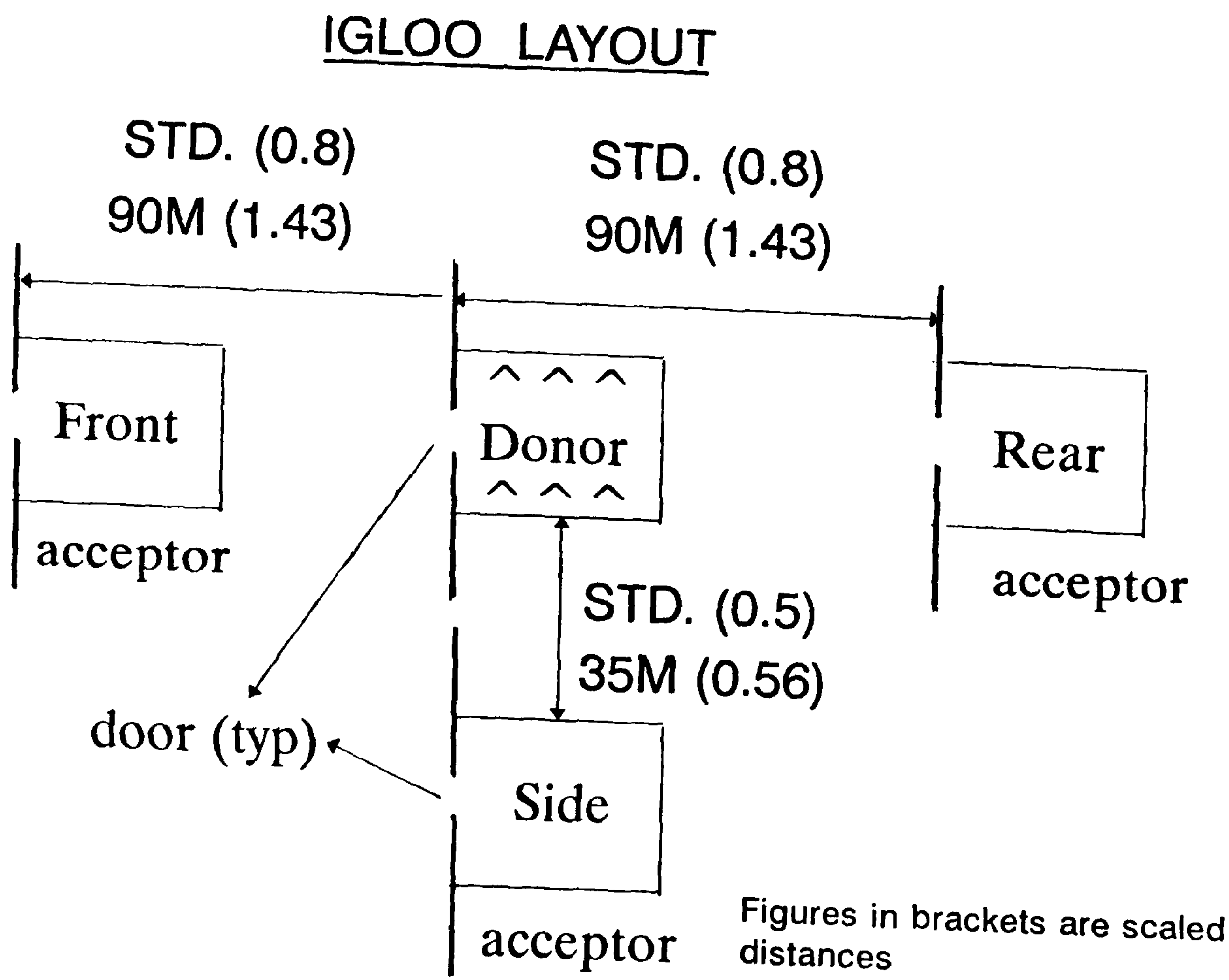

IGLOO LAYOUT
STD. (0.8)
90M (1.43)
STD. (0.8)
90M (1.43)
Front
acceptor
Donor
Rear
acceptor
STD. (0.5)
35M (0.56)
door (typ)
Side
acceptor
Figures in brackets are scaled distances

FIG. 13

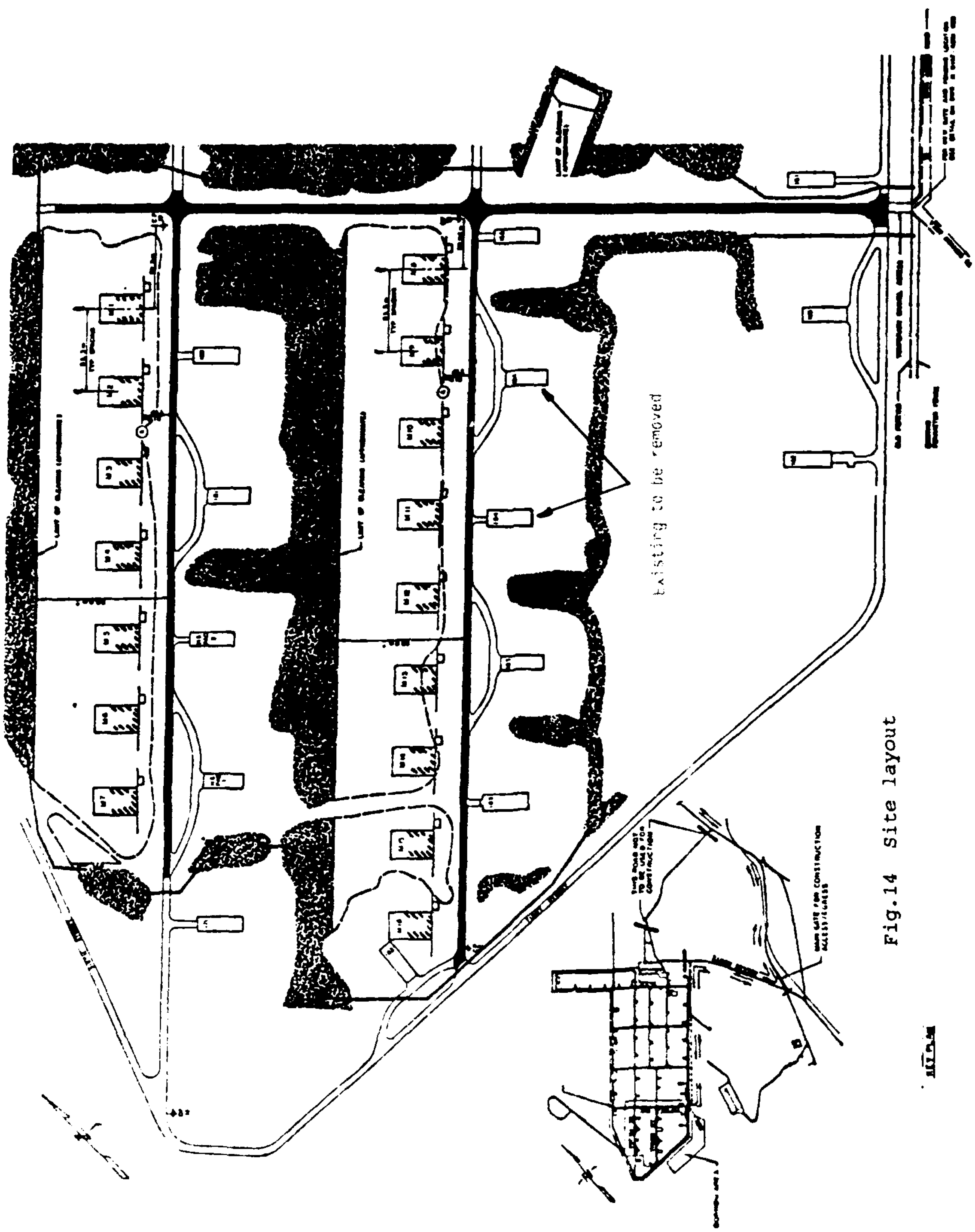


Fig.14 Site layout

DYNAMIC DESIGN

(BLAST LOADS)

(1) STANDARD IGLOO HAS BEEN DESIGNED (DYNAMICALLY) AS "ACCEPTOR" STRUCTURES FOR THE FOLLOWING MAXIMUM BLAST LOADS AT MINIMUM SEPARATION DISTANCES OF 35M (SIDE TO SIDE) AND 90M (FRONT TO REAR) BETWEEN IGLOOS, WITH EXPLOSIONS OCCURRING ACCIDENTALLY IN ADJACENT IGLOOS, TERMED AS "DONOR" STRUCTURES:

ELEMENTS OF "ACCEPTOR"	LOCATION OF "DONOR"	PRESSURE (KPa)	IMPULSE (KPa MSEC)	DURATION (MSEC)
. HEADWALL ¢ FRONT DOOR	REAR	420	7,980	38
	FRONT	275	11,825	86
	SIDE	400	7,600	38
. SIDEWALL	REAR	550	9,625	35
	FRONT	70	4,550	130
	SIDE	530	7,950	30
. REARWALL	REAR	700	10,850	31
	FRONT	50	4,400	176
	SIDE	400	7,600	38
. ROOF SLAB	REAR	550	9,625	35
	FRONT	70	4,550	130
	SIDE	400	7,600	38

. SLAB ON GRADE (LIVE LOAD) 50 KPa

NOTE: 100 KPa = 1 BAR

FIG.15

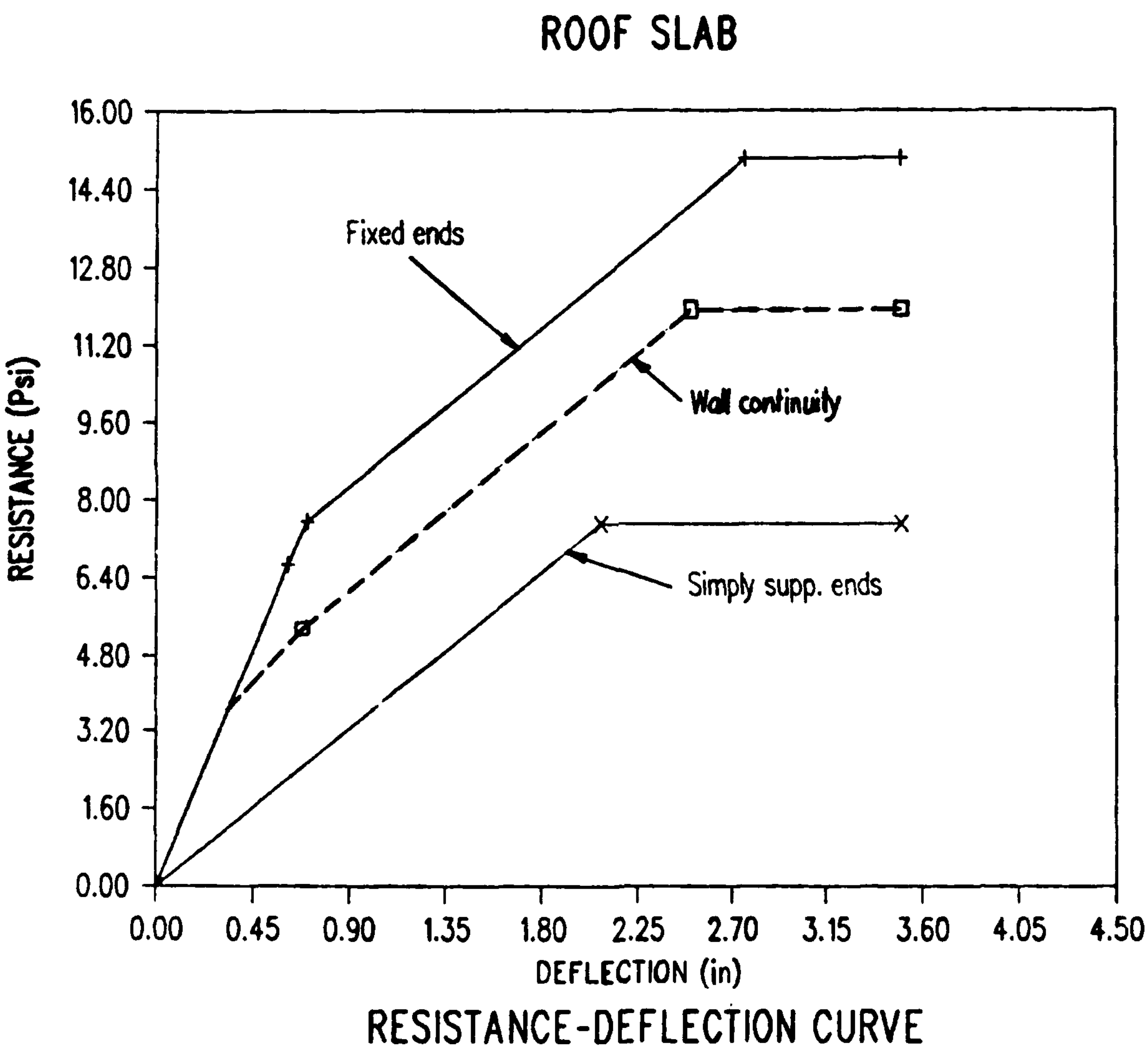

ROOF SLAB
RESISTANCE (Psi)
16.00
14.40
12.80
11.20
9.60
8.00
6.40
4.80
3.20
1.60
0.00
Fixed ends
Wall continuity
Simply supp. ends
0.00
0.45
0.90
1.35
1.80
2.25
2.70
3.15
3.60
4.05
4.50
DEFLECTION (in)
RESISTANCE-DEFLECTION CURVE

FIG.16

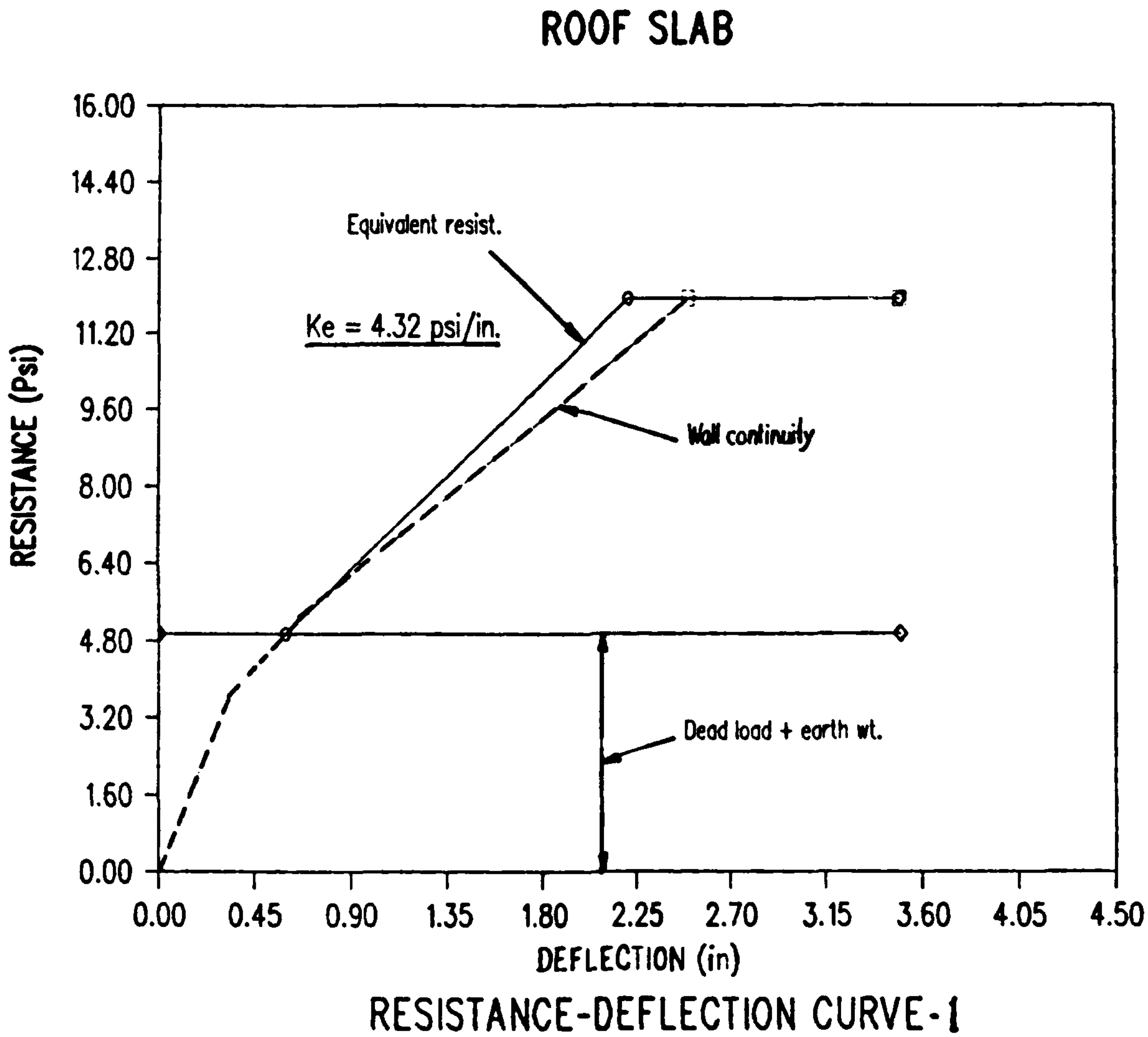
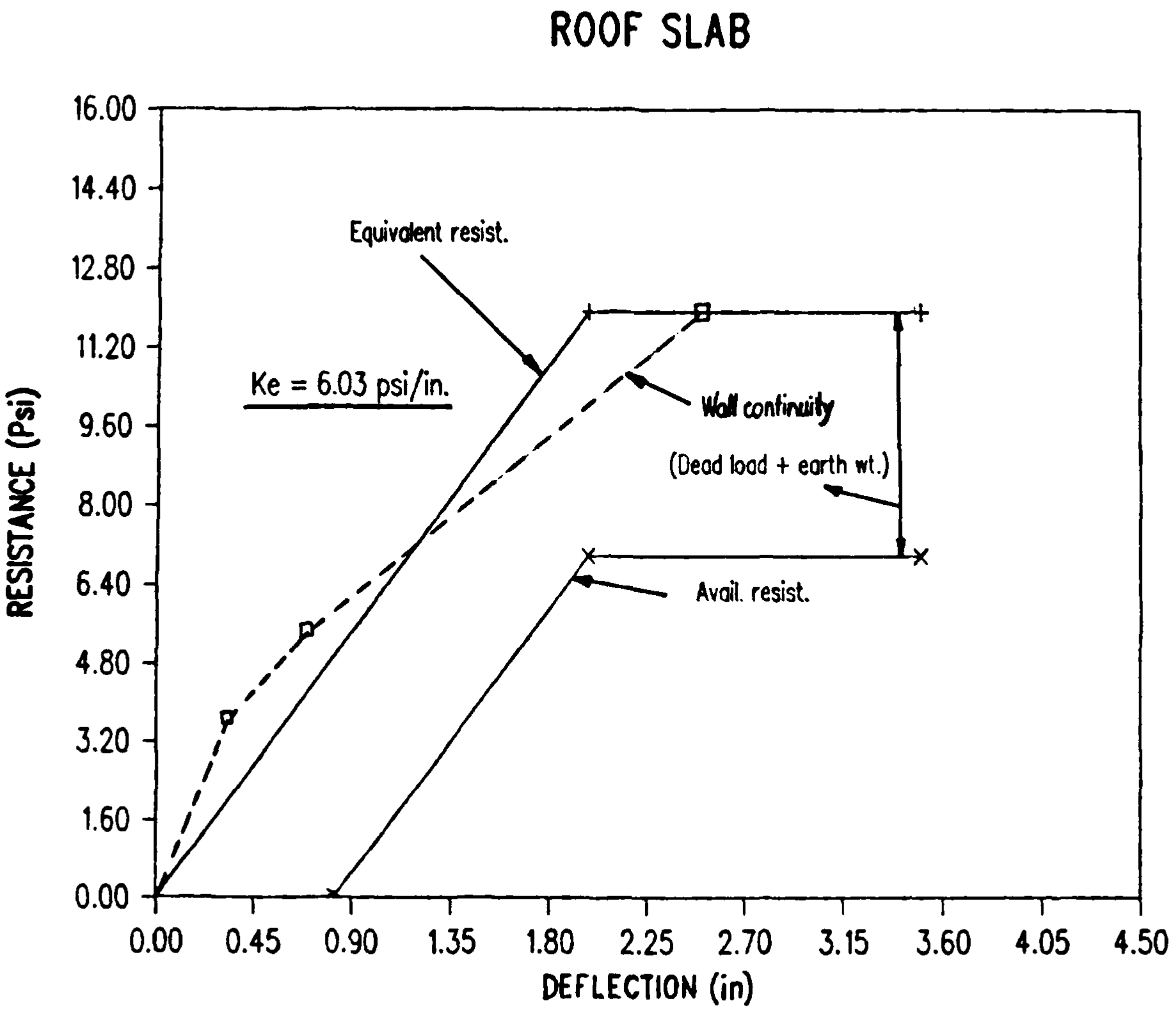

ROOF SLAB
16.00
14.40
12.80
11.20
9.60
8.00
6.40
4.80
3.20
1.60
0.00
RESISTANCE (Psi)
Equivalent resist.
Ke = 4.32 psi/in.
Wall continuity
Dead load + earth wt.
0.00
0.45
0.90
1.35
1.80
2.25
2.70
3.15
3.60
4.05
4.50
DEFLECTION (in)
RESISTANCE-DEFLECTION CURVE-1

FIG.17



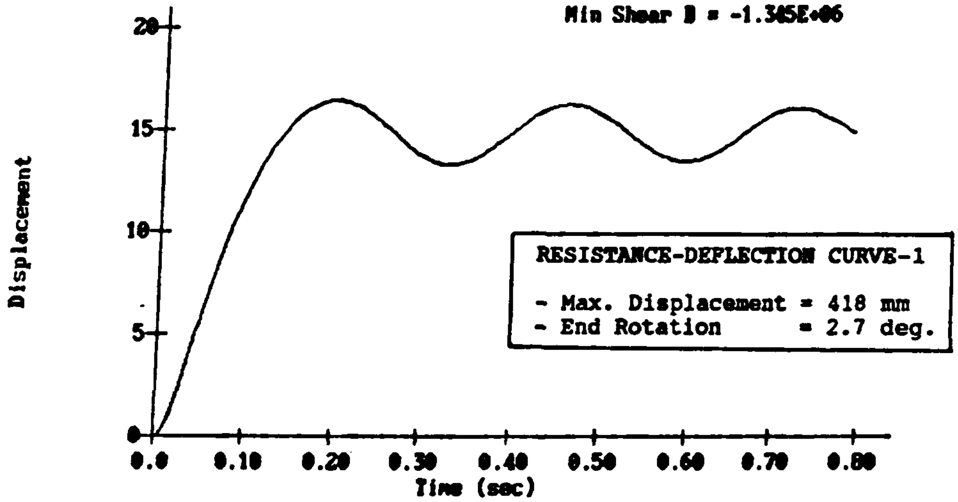
RESISTANCE-DEFLECTION CURVE - 2

FIG.18

Roof Slab

Equiv. Elastic Displac. = 1.618E+00
Max Displacement = 1.645E+01
Min Displacement = 6.066E-02
Time of Max Displacement = 1.960E-01
Time of Min Displacement = 3.500E-03
MU = 1.016E+01

Max Force = 6.559E+07
Min Force = 0.000E+00
Max Resistance = 5.731E+06
Min Resistance = -5.381E+06
Max Shear A = 2.973E+06
Min Shear A = -5.381E+05
Max Shear B = 5.957E+06
Min Shear B = -1.345E+06



Roof Slab

Equiv. Elastic Displac. = 1.159E+00
Max Displacement = 1.581E+01
Min Displacement = 6.060E-02
Time of Max Displacement = 1.925E-01
Time of Min Displacement = 3.500E-03
MU = 1.364E+01

Max Force = 6.559E+07
Min Force = 0.000E+00
Max Resistance = 5.731E+06
Min Resistance = -5.381E+06
Max Shear A = 2.982E+06
Min Shear A = -5.381E+05
Max Shear B = 5.978E+06
Min Shear B = -1.345E+06

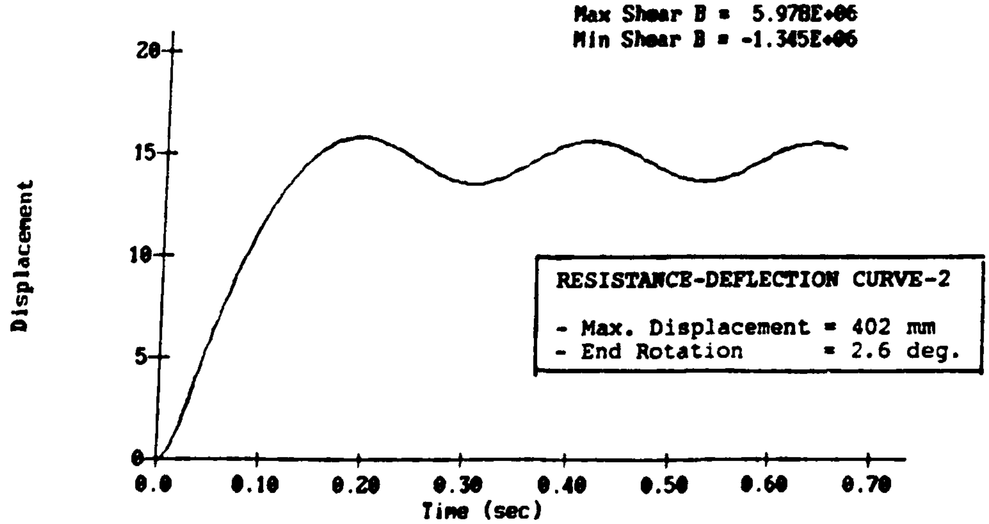
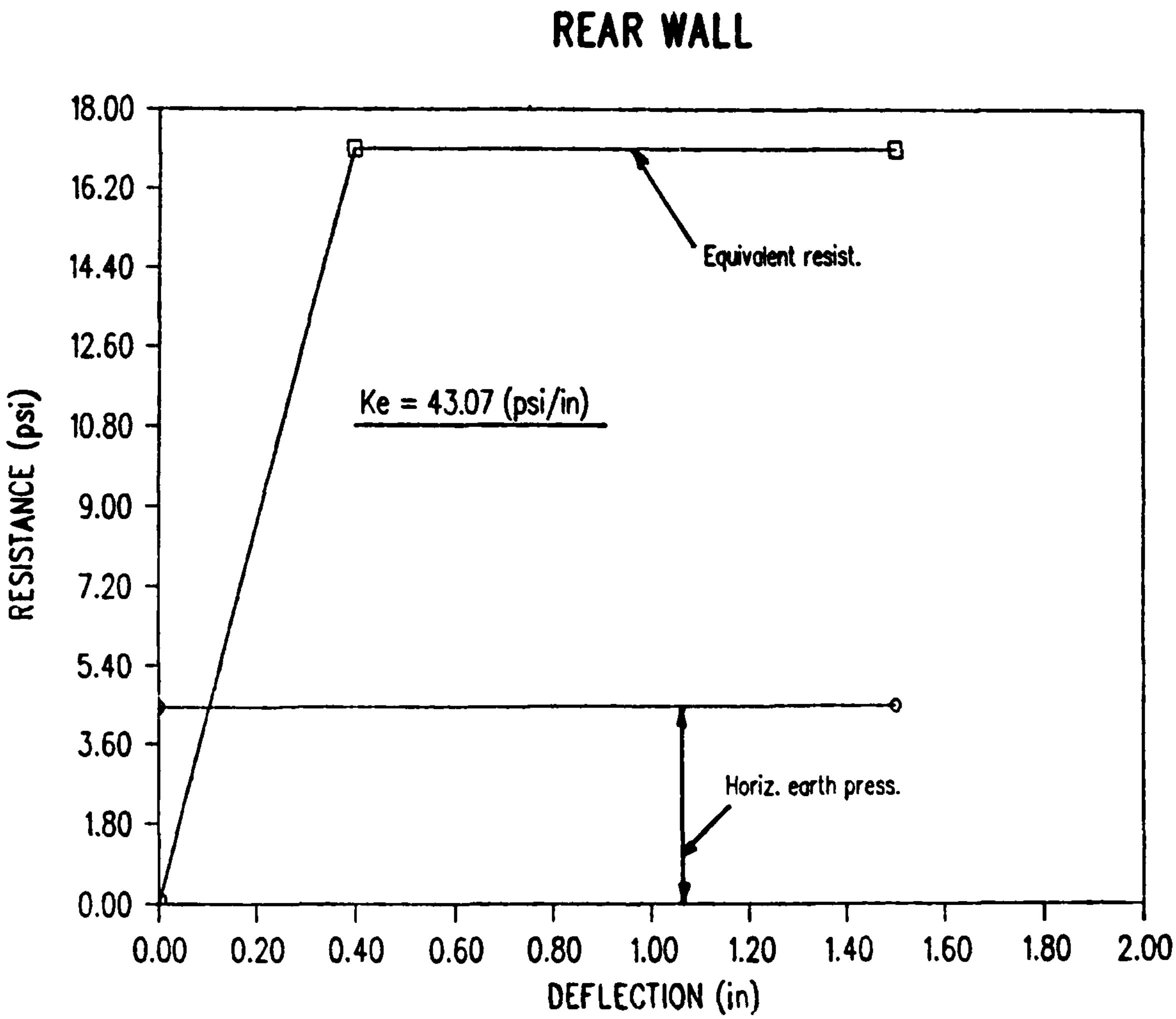


FIG.19



RESISTANCE-DEFLECTION CURVE

FIG.20

RESULTS

(DYNAMIC DESIGN)

ELEMENT	SIZE	FLEXURE +AXIAL		SHEAR	
		Max displ. (mm)	End rotation (degrees)	Actual (mpa)	Allowable (mpa)
Roof Slab	850 mm thick 30M @ 200 & 25M @ 200 (top & bot. bothways)	402	2.6	1.19	1.11
Side Walls	600 mm thick 25M @ 200 (vert.) 15M @ 200 (horz.)	221 * {120}	3.7 * {2}	0.99	0.99
Rear Walls	600 mm thick 30M @ 200 (vert.) 15M @ 200 (horz.)	222 * {121}	3.7 * {2}	1.25	0.99
Front Wall	600 mm thick 30M @200 (vert.) 25M @ 200 (horz.)	37	0.9	0.95	0.99
Door	W 250 x 39 @ 400 8 mm plates-2nos	122	2.6	379 kn	388 kn

NOTES: * Figures allow for mass of earth = 1.2m width behind wall.
{ } Figures in brackets allow for mass of earth = 1/2 height of wall behind wall.

Fig.21

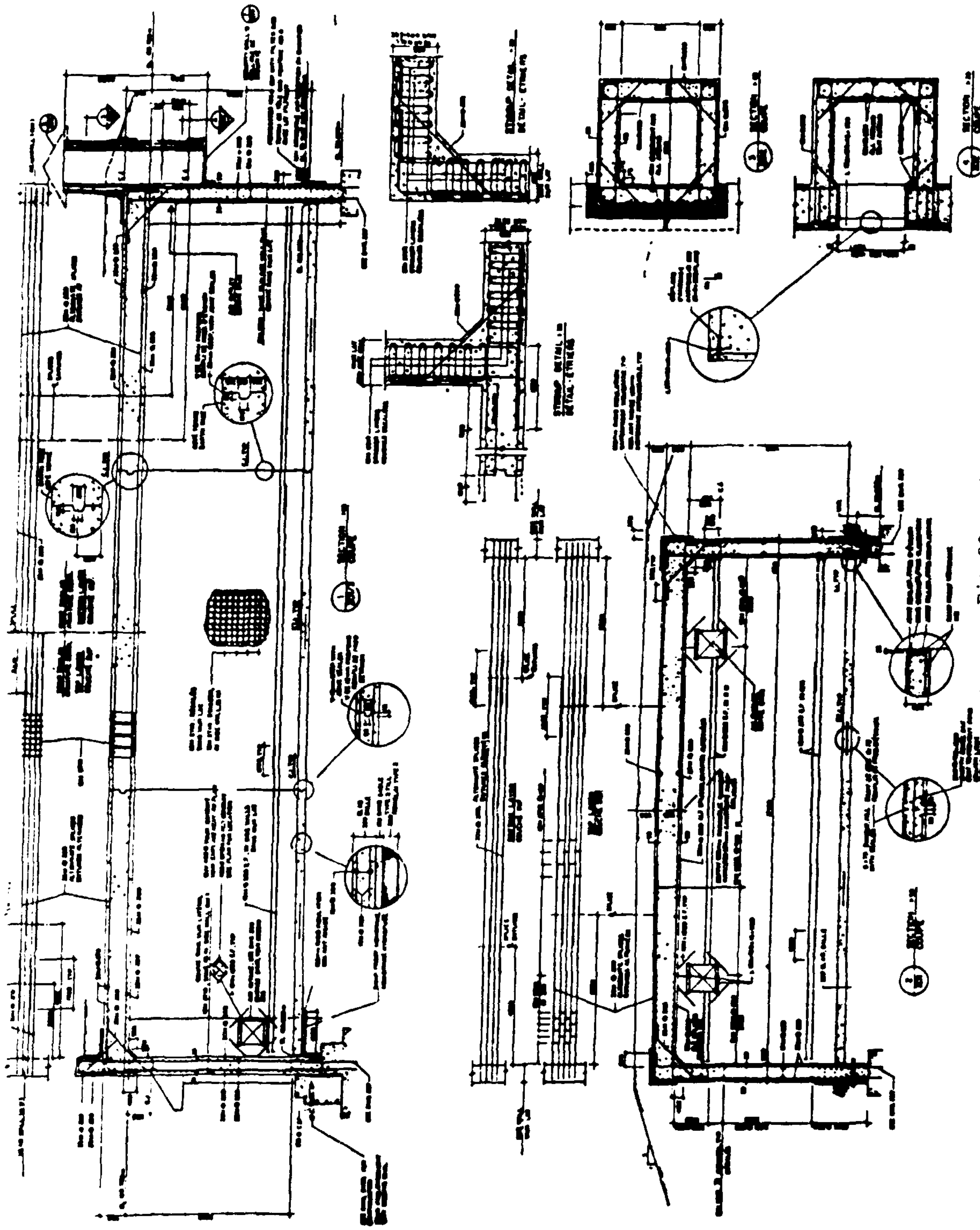


Fig.22 Reinforcement details

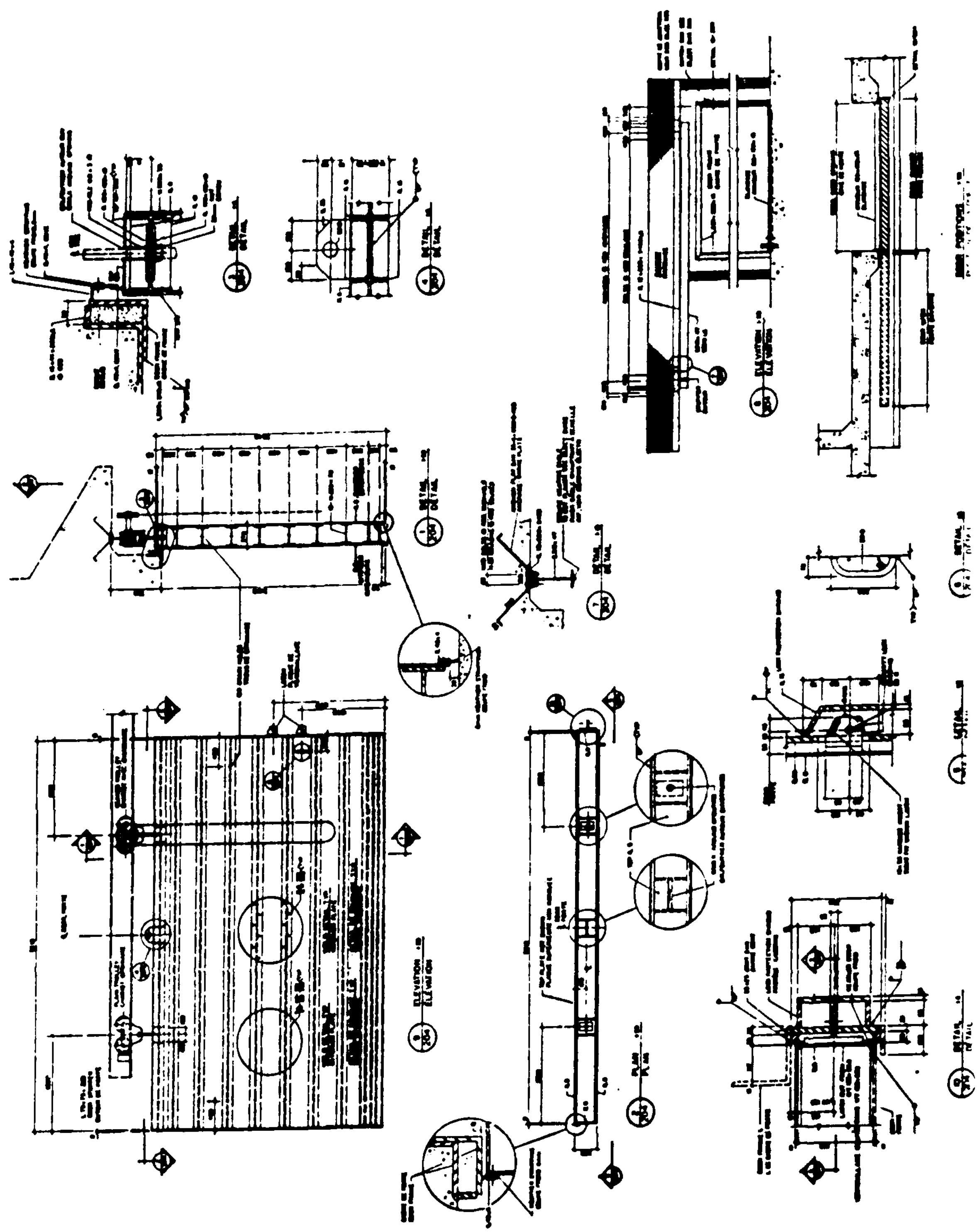
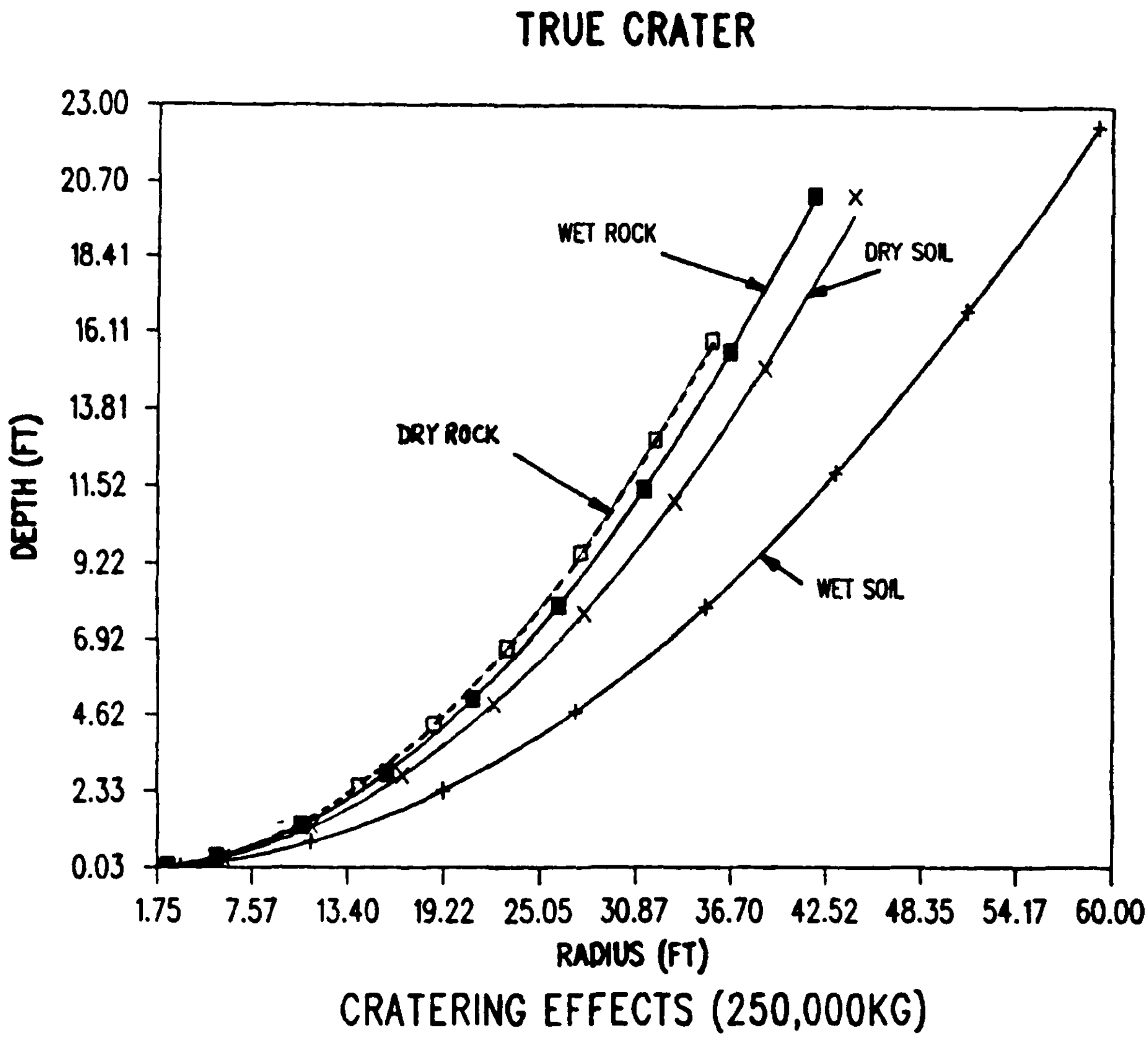
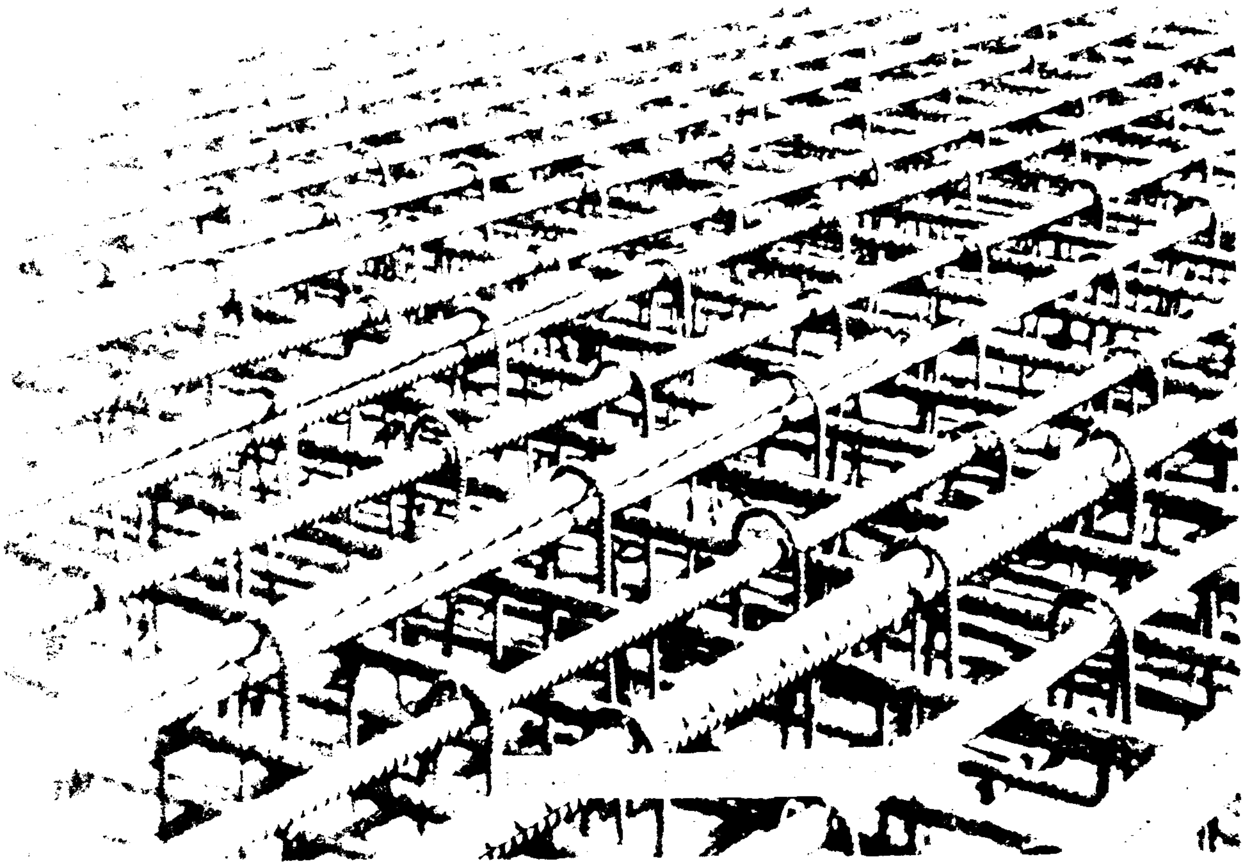


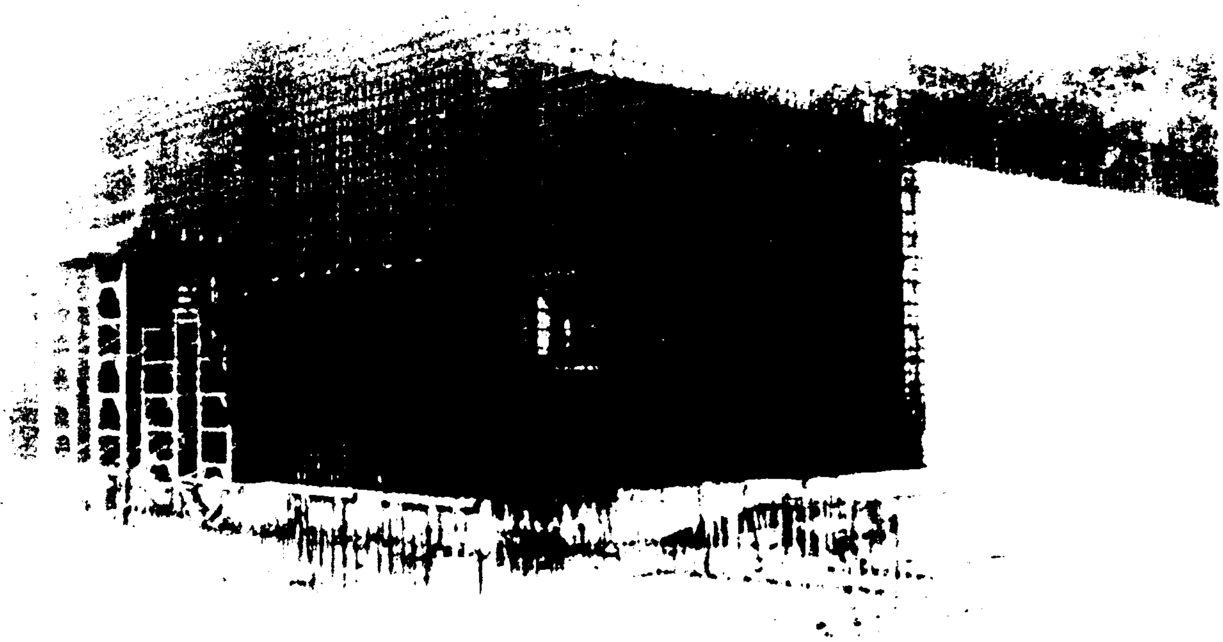
Fig.23 Sliding door details

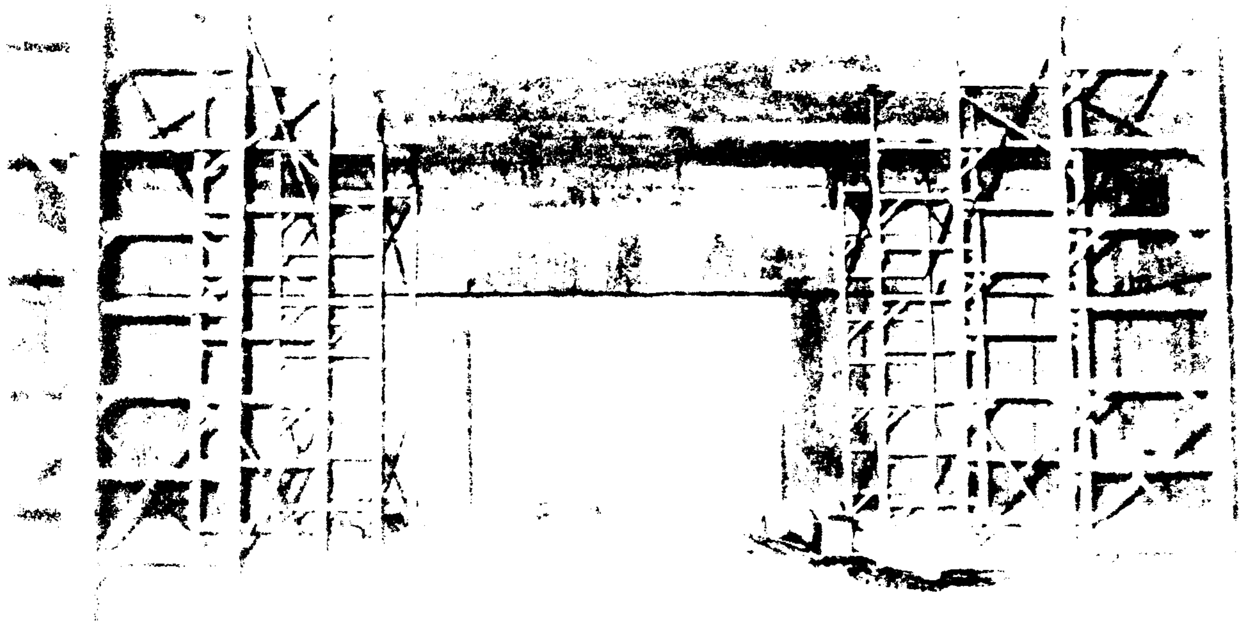


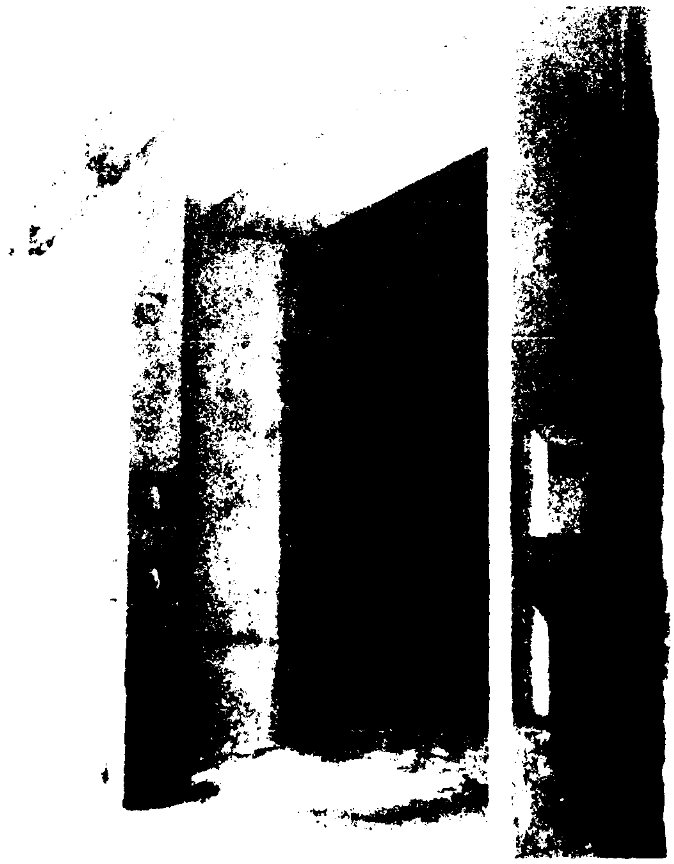
TRUE CRATER
23.00
20.70
18.41
16.11
13.81
11.52
9.22
6.92
4.62
2.33
0.03
DEPTH (FT)
WET ROCK
DRY SOIL
DRY ROCK
WET SOIL
1.75
7.57
13.40
19.22
25.05
30.87
36.70
42.52
48.35
54.17
60.00
RADIUS (FT)
CRATERING EFFECTS (250,000KG)

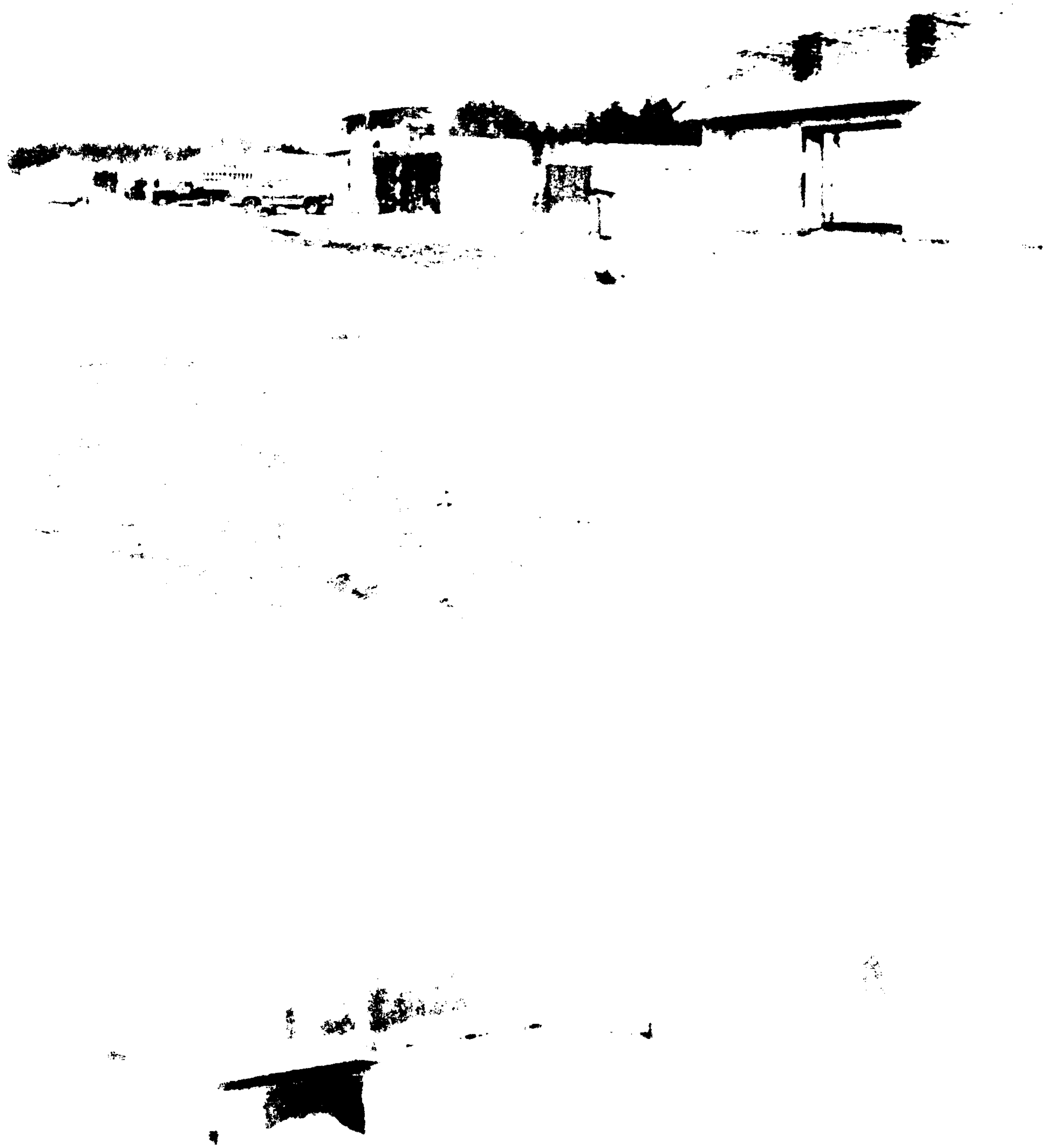
Fig.24











CONCRETE STRENGTH

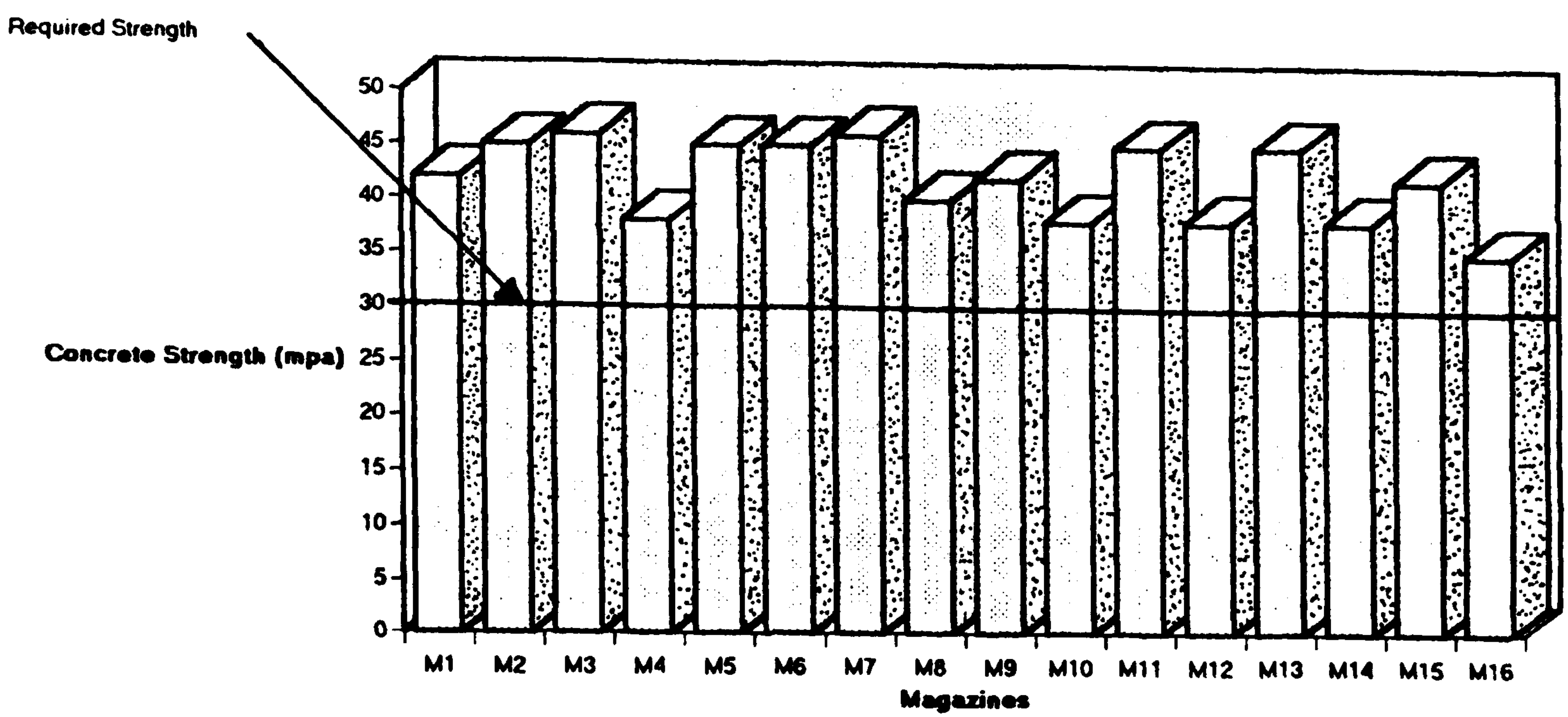


Fig.31

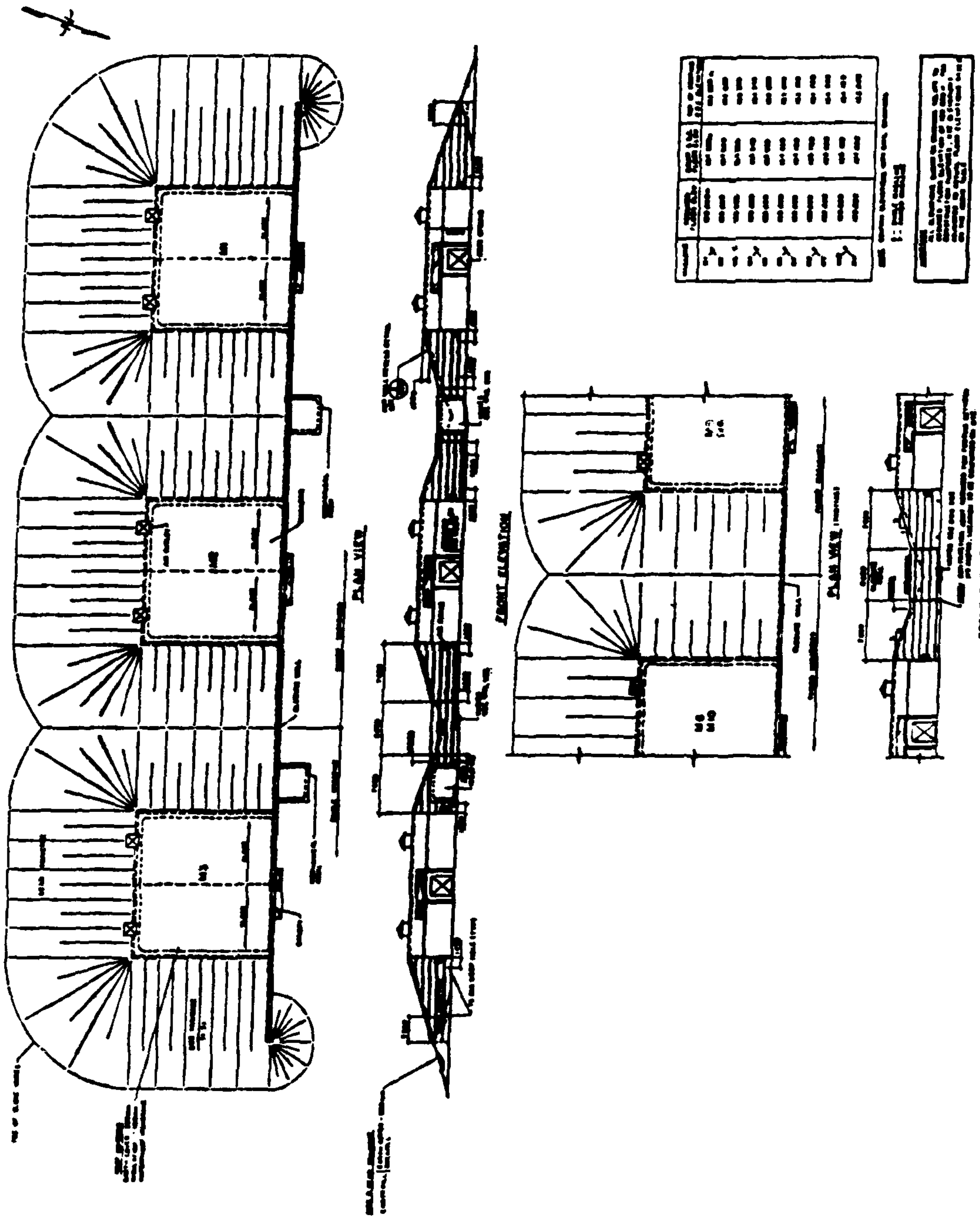


Fig.32 40,000 kg. NEQ igloos - plan

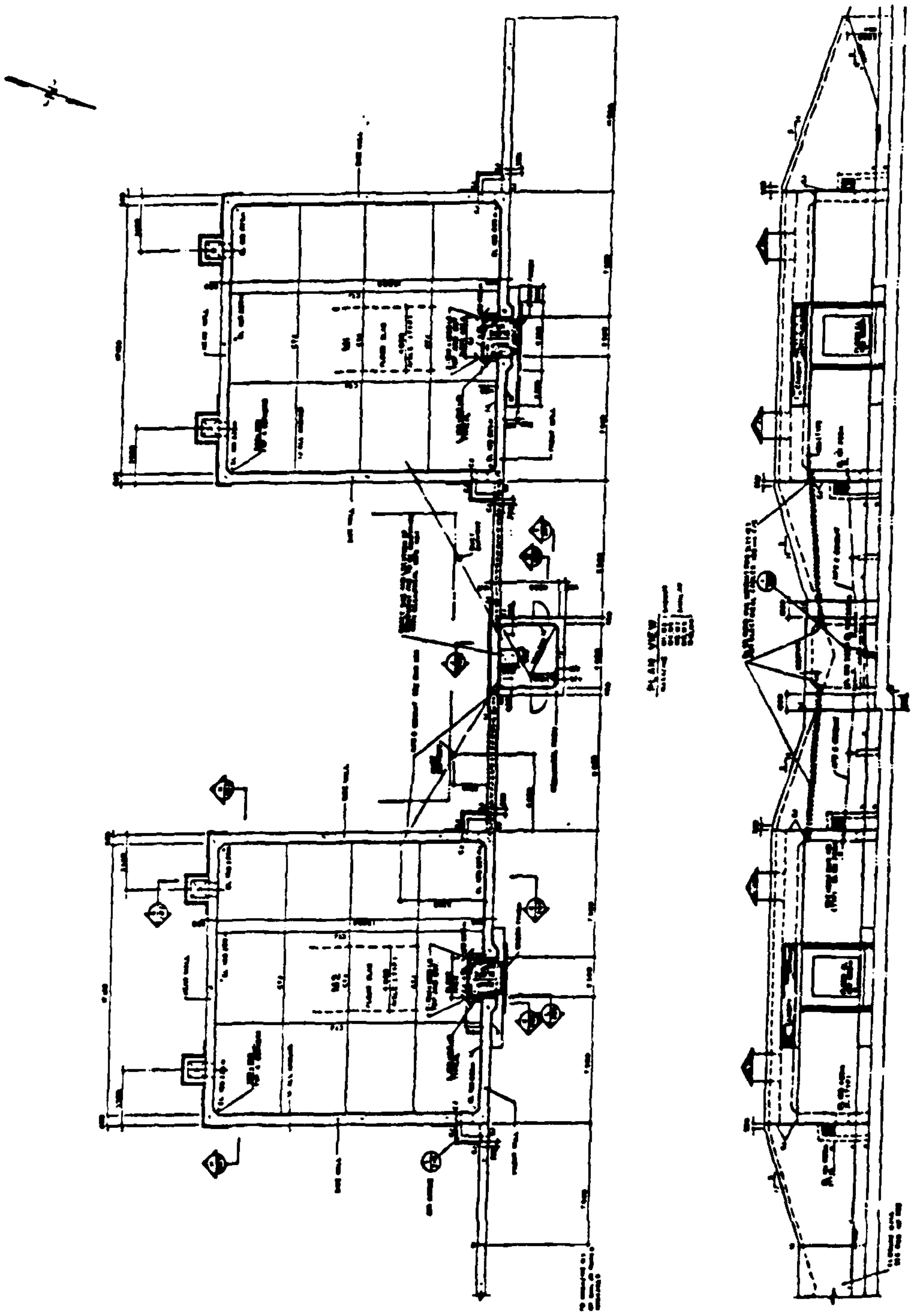


Fig.33 40,000 kg. NEQ igloos - details

CANADIAN IGLOOS

UNIT COSTS

SIZE(W,L,H)m (NOS.)	VOLUME (Cu.M)	NEQ/IGLOO (Kg)	COST/ (Cu.M)	COST/ (Kg of NEQ)	REMARKS
18X15.9X4.9 (1)	1398	75000	$ 539	$ 10.04	* Consn.1987 * Crane
16.8X18X6 (4)	1814	45000	$ 378	$ 15.00	* Consn.1990 * Crane
17.1X28.7X5.6 (1)	2748	250000	$ 405	$ 4.50	* Consn.1990
17.1X28.7X5.6 (16)	2748	250000	$ 330	$ 3.63	* Consn.1990

Fig.34

DEVELOPMENT OF A NEW RECTANGULAR BOX-SHAPED STANDARD AMMUNITION STORAGE MAGAZINE

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Twenty-Fifth Department of Defense Explosive Safety Seminar
Anaheim, California
18-20 August 1992

ABSTRACT

A new, earth-covered, standard magazine for the storage of ammunition and explosives is being developed by the U. S. Army Corps of Engineers. The new magazine is to be constructed using the Blast and Fragment Resistant (BFR) wall system, also known as the Agan Steel Panel (ASP) system. The magazine is a rectangular box structure with a flat roof. It is anticipated that this magazine will be approved as a standard magazine for storage of up to 500,000 pounds net explosive weight, in accordance with DOD 6055.9-STD. If approved, it will become the first standard magazine approved on the basis of design using the methods in the U. S. Army Technical Manual TM 5-1300. The magazine will permit storage of large quantities of explosives at standard intermagazine distances, and it will provide the advantages of a rectangular shape rather than a circular or oval arch.

This paper discusses the background behind the development of the new box-shaped magazine, the basis of design and blast loading assumptions used, the configuration and details of the new magazine, and advantages over the existing standard magazine designs.

INTRODUCTION

The Blast and Fragment Resistant (BFR) wall system was developed for use in structures subjected to the effects of conventional weapons. The BFR system is a composite structure of exterior steel face panels, tied together with internal, diagonal steel lacing panels, and filled with concrete. The system has been extensively tested for its resistance to explosions of in-

dividual and small groups of conventional munitions. Tests have shown that the system provides highly ductile behavior when subjected to both static and dynamic loads. It has also been shown to be extremely resistant to fragment penetration.

The BFR system was suggested as a construction material for standard, earth-covered, ammunition storage magazines. The specific configuration and general design details for this magazine were proposed by the inventor of the system to the U. S. Department of Defense Explosive Safety Board (DDESB). The Huntsville Division, U. S. Army Corps of Engineers, was tasked to evaluate the BFR box magazine concept. The scope of work for this effort was divided into two phases. In the first phase, the BFR system was to be evaluated to determine its feasibility for use in a standard magazine. The second phase of this effort was to complete the actual definitive design for the "Magazine, Steel and Concrete Box, Earth-Covered," referred to herein as the BFR magazine. The design was to include drawings similar in scope and detail to existing magazine standard drawings, technical specifications, a design analysis, and a cost estimate.

This paper summarizes BFR magazine evaluation and design effort. It presents a brief definition of a DDESB standard magazine and of the BFR wall system. The proposed and final magazine configurations are presented. Structural analysis and design assumptions are presented. The basis of design for the new magazine is shown, and advantages over existing magazine designs are outlined.

The reader should note that the term "standard" is used for two different meanings in this paper. A "standard magazine" is a earth-covered structure for the storage of ammunition and explosives, approved by DDESB, as described below. A "standard design" is a definitive, site-adaptable design of a facility, including detailed drawings and specifications.

DOD STANDARD MAGAZINES

DOD 6055.9-STD, "DOD Ammunition and Explosive Safety Standards" [1][1], defines a standard, earth-covered magazine as a structure approved for the storage of munitions or explosives containing an equivalent weight of up to 500,000 pounds of TNT. The minimum separation distances between standard magazines are based on the net explosive weight (NEW), in pounds, stored in the magazines. The minimum side-to-side spacing is 1.25 times the cube root of the NEW. The minimum front-to-rear spacing is 2.0 times the cube root of the NEW. The standard magazines have been approved based on their performance in actual explosive tests. It has been proven, in full-scale tests, that these structures will prevent propagation of an accidental explosion between adjacent magazines. A number of designs have been approved by DDESB as standard magazines. These are listed in DOD 6055.9-STD. The standard magazine approved by DDESB for all new construction in the U. S. Army is the earth-

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1. Numbers in brackets refer to references listed at the end of this paper.

covered, concrete, oval-arch magazine found in U. S. Army Corps of Engineers Standard Drawings 33-15-74 [2].

The ultimate goal of this development effort is to obtain approval of the BFR magazine, by DDESB, for use as a standard magazine. However, it is our goal to develop a magazine that will be approved on the basis of design alone rather than testing. If approved, the BFR magazine will become the first standard magazine to be approved without actual explosive testing.

BFR WALL SYSTEM DEFINITION

The BFR wall system is a composite of steel and concrete. The exterior surfaces of a BFR wall consist of thin, lightly corrugated, steel face panels. These panels are usually manufactured in widths of 200, 250 and 300 mm (approximately 8, 10 and 12 inches) and lengths as required. Corresponding thicknesses of these panels are 0.8, 1.0 and 1.2 mm, respectively. The face panels interlock at ribs along their vertical edges to form a continuous exterior steel surface. The front and rear face panels are tied together using diagonal steel panels, referred to herein as lacing panels. The lacing panels are arranged between the face panels in a zig-zag pattern and are attached to the face panels with sheet-metal screws. The lacing panels vary in width to match the specific face panel dimensions and are generally 0.6 mm thick. This assembly of steel sheets is filled with a high-slump concrete mix. Holes are provided in the lacing panels to allow the flow of concrete between the panels. When assembled, the thickness of the wall is the same as the width of the individual face panels. Therefore, finished BFR walls are available in thicknesses of 200, 250 and 300 mm. The BFR system also includes corner and end sheets for forming wall intersections and closing ends of walls. The overall assembly of the system is illustrated in Figure 1.

PROPOSED BFR MAGAZINE CONFIGURATION

The details of the proposed BFR magazine were provided in Reference 3. The proposed magazine was an earth-covered box structure, 24 feet wide, with a clear ceiling height of 11'-2" and variable length. The proposed headwall was a 300 mm thick BFR wall. The side and rear walls were to be 250 mm thick BFR elements. The roof slab was essentially a conventional reinforced concrete slab, 13 inches thick, using the 300 mm wide BFR face panels on the inner surface as part of the slab reinforcement and as an anti-spalling plate. The structure would be covered with earth, a minimum of two feet thick over the roof, surrounding the side and rear walls, and sloping away from the roof on an incline of 2 horizontal to 1 vertical. The retaining walls, or wingwalls, to support the earth cover at the front of the structure, were also to be 300 mm BFR walls. All foundations were normally reinforced concrete footings. There were two options for the door on the front of the magazine. The first option was to use the sliding, single-leaf steel door, with its accompanying concrete pilasters and header, as detailed in the U. S. Army 33-15-74 standard design. The second option was to use a door constructed of the 200 mm thick BFR section, spanning horizontally, and supported by two BFR pilasters located inside the headwall at the door jambs.

FEASIBILITY STUDY

The first phase of this development effort was a feasibility study [4]. The primary objective of the study was to determine whether the proposed BFR magazine could be used as a standard magazine. As stated above, this magazine must afford the stored explosives sufficient protection to prevent propagation of an explosion, from one magazine to another, at standard intramagazine distances. Therefore, the feasibility study required an independent structural analysis of the BFR concept. As stated above, the ultimate goal of this effort was to develop a structure that would be approved as a standard magazine based only on design. Therefore, we made significantly conservative assumptions about both blast loadings and structural performance.

The BFR magazine structure was analyzed for both static and dynamic loads. The static loads were simply the weight of the structure itself plus the weight of the earth cover. The dynamic loads were those that would be expected from an actual explosion in an adjacent magazine. For the headwall and doors, we used the U. S. Army standard headwall loading derived from the ESKIMO III test [5]. However, for standard magazines, there are no similar loads derived for the buried elements of the structure. In its analysis of the structure, Reference 3 used overpressure loads derived from AC/258, "Manual for NATO Safety Principles for the Storage of Ammunition and Explosives" [6]. These were the predicted overpressure loads on a non-buried, rectangular structure subjected to an explosion of 500,000 pounds of TNT at standard intermagazine distances. These loads were used for our independent analysis. The overpressure loads used for each structural element are given in Table 1.

For the analysis, it was assumed that the BFR walls would perform essentially the same as equivalent, normally reinforced concrete elements. The analysis for static loads was carried out in accordance with ACI 318-89, "Building Code Requirements for Reinforced Concrete" [7]. Analysis for the dynamic loads was performed using the procedures and requirements of the revised U. S. Tri-Service Manual, "Structures to Resist the Effects of Accidental Explosions," TM 5-1300 [8]. Structural details which define the general behavior of the BFR elements were drawn from References 3 and 9. We assumed the face panels to be the principal flexural reinforcement for the elements. Only the portion of the face panels actually on the external faces of the elements were considered. The lacing panels were assumed to behave solely as shear reinforcement. This is a conservative approach because it neglects a portion of the steel that is actually in the wall and does not account for the increased ductility of BFR walls over similar concrete walls.

The dynamic analysis of each element was performed using the computer programs BARCS and SOLVER. BARCS [10] analyzes concrete slabs and beams subjected to blast loads in accordance with the 1969 edition of TM 5-1300 [11]. This program was used to compute moment capacities and resistance-deflection functions for each BFR element. The equations in BARCS that perform these calculations are also valid for the 1990 edition of TM 5-1300. SOLVER [12] is a single-degree-of-freedom (SDOF) dynamic analysis program. It computes velocity, acceleration, and displacement of a SDOF system over time. The

results from BARCS and the overpressure loads were used as inputs to SOLVER to determine the maximum dynamic response of each element. The damping ratio used in the analysis was 20% of critical damping.

The maximum deflection limit used as the criteria for incipient failure of the BFR elements was a support rotation of 13.5 degrees. This limitation is drawn from the results of a static test of the 250 mm thick BFR element [3]. In that test, the BFR element experienced the 13.5 degree support rotation without failure of the plastic hinge. Therefore, this failure criteria is conservative.

The preliminary study demonstrated that the BFR system would be an outstanding material to use for standard magazines. The BFR headwall, wingwalls, side and rear walls of the magazine were found to be strong enough to support the static loads and resist the assumed blast loads. The maximum deflections of these elements were less than the support rotation limit. The lacing panels provided sufficient reinforcement to prevent shear failure due to diagonal tension stresses. However, the analysis showed that the BFR walls would not withstand the direct shear stresses at the supports. Diagonal bars would be required as direct shear reinforcement in the final design. The analysis indicated that the proposed roof slab would not comply with the ACI design code, nor would it support even the static loads. A new roof design would be needed. The study established that the BFR door, with additional reinforcement, would withstand the overpressure loads. However, the accompanying BFR pilasters would need to be essentially the same as those used for the sliding steel doors. The weight of the BFR door was more than twice that of the steel door, 10,000 pounds vs. 3,800 pounds, making it harder to operate manually. Also, the BFR door required a track mechanism at the threshold that would be difficult to maintain at some sites and in a long-term storage environment where maintenance might not always be reliable. Therefore, we recommended using the steel doors from existing magazine designs.

VALIDATION OF ANALYSIS METHODS

As part of the feasibility study, the results of several explosive tests of the BFR system were examined. These tests were used to verify the both the general structural analysis methods and, specifically, the assumption that the BFR wall can be predicted to behave essentially the same as an equivalent reinforced concrete slab. We performed an analysis of the BFR structure in each test case using the methods described above. We then compared the computed response to actually performance. This comparison revealed that the predicted deflections were consistently larger than the actual deflections. It also indicates that the BFR walls actually perform better than comparable concrete walls. This confirms that using the methods in TM 5-1300 and assuming the walls to be normally reinforced concrete is conservative.

As mentioned above, our structural analysis used a damping ratio of 20% of critical damping. This is the damping ratio proposed in Reference 3. It is an unusually high degree of damping for normal reinforced concrete elements. A ratio of 3% to 5% is typical, and damping is usually only applied to elastic range of deflections. To determine a usable, reliable damping ratio

for design, the explosive test results were again compared to response predicted by the SDOF model. For the analysis, we used the total area of the steel face panels for flexural reinforcement. The results showed that damping ratios of 30% to 50% or even higher were applicable, over the entire range of response, not just the elastic range. To be conservative, 20% damping would be used for the analysis and design calculations.

FINAL MAGAZINE DESIGN

The second phase of the BFR magazine development effort was to produce actual design drawings and details for the magazine. Again, the BFR walls were assumed to perform the same as equivalent reinforced concrete sections. The entire area of the steel face panels was used as flexural reinforcement. Static and dynamic analysis were performed using the same methods as in the feasibility study. The effects of the earth cover were included in the loads and as part of the mass responding to the dynamic loads. However, soil arching and any resulting attenuation of blast effects were neglected, which is quite conservative.

The headwall, side walls, and rear wall were designed to be one-way elements, spanning vertically, with pinned supports. The roof slab was also detailed to be a one-way element, with pinned supports, spanning across the width of the magazine. The one-way spans make it possible to construct magazines in varying lengths with no changes in details. With pinned supports, the walls and roof have less total resistance than if moment-resisting supports were used. This lower resistance in turn reduces the required shear resistance and shear reinforcement requirements.

Design overpressure loads were derived from actual magazine explosive test data. Sources of data included the ESKIMO series of tests [5, 13, 14, 15, 16], the U. S. Air Force Modular Igloo Test [17], and 1/50 scale tests by the Ballistic Research Laboratory [18]. For each structural element, observed overpressure, duration, and impulse data were compiled from the test reports. Where applicable, the data were scaled up to the maximum charge weight of 500,000 pounds of TNT. The data were compared, and the most reasonable and consistent dynamic load was selected for each element. The design loads are listed in Table 2 below.

The intent of the design is to prevent an explosion of 500,000 pounds of TNT in one magazine from creating a sympathetic explosion in adjacent magazines. As a criterion to prevent this propagation, the BFR magazine was designed to remain standing, although suffering severe damage, after such an explosion. For design of the headwall, side and rear walls, and roof, support rotations were limited to 12 degrees, as prescribed in TM 5-1300. This was a design criteria limit. Computed support rotations, given in Table 3 below, were significantly less than 12 degrees. In the event of an accidental explosion, only moderate structural damage is expected to occur. All of the structural elements are expected to remain intact and in place, which should ensure that the explosion does not propagate between magazines.

The steel doors and their supporting pilasters and header were adapted from existing standard magazine designs. Since these doors were designed for the headwall blast load, no analysis of the doors themselves was performed. The pilasters and header are conventional reinforced concrete beams. Since the existing standard reinforced concrete headwall is an two-way element and the BFR headwall is a one-way element, the new pilasters and header were analyzed in detail. All connections were assumed to be pinned, to reduce the ultimate resistance and shear requirements and eliminate the need for moment-resistant foundations. The header and pilasters were designed using the same methods as the walls, as described above. In order to prevent the door from flying into the magazine, support rotations of the pilasters and header were limited to 2 degrees.

The 300 mm BFR wall section was used for the wingwalls. A conventional reinforced concrete foundation was provided. This foundation varies in width with the height of the wall. The wall as designed as a typical cantilever retaining wall. Since the BFR steel panels do not extend into the foundation, additional reinforcement was provided at the base of the wall to provide moment continuity between the wall and the foundation.

FINAL BFR MAGAZINE CONFIGURATION

The final configuration of the BFR magazine is similar to the proposed concept. The interior dimensions of the magazine are the same as originally proposed: 24 feet wide with an 11'-2" minimum clear ceiling height. The length of the magazine can vary from 20 feet to 90 feet; a typical length of 80 feet is shown on the design drawings. The headwall and wingwalls are made of the 300 mm BFR wall cross section. The side and rear walls are the 250 mm BFR cross section. The roof is a concrete slab, 18 inches thick, with a layer of reinforcement in each face. The BFR face panels were omitted from the interior surface of the roof slab, primarily because it will be less expensive to use conventional formwork. The floor of the magazine is a 6-inch concrete slab, sloping toward the front of the magazine. Foundations are normal reinforced concrete strip footings. An elevation view of the BFR magazine is shown in Figure 2. A section through the magazine is shown in Figure 3.

In general, the BFR face panels and lacing panels form the principal flexural and shear reinforcement for the structure. At the base of each wall, "starter bars" extend from the foundation into the wall. These bars are equal in cross-sectional area to the steel face panels. Their length is sufficient to provide static moment capacity, in accordance with ACI 318-89, but not long enough to provide dynamic moment resistance as defined by TM 5-1300. This arrangement provides moment continuity for static loads and during construction, but effectively retains the pinned condition for dynamic loads. Similarly, the roof reinforcement is extended a short distance into the headwall, side walls and rear walls. Again, this provides some moment capacity for static loads but maintains the pinned connection for dynamic loads. Structural details at the headwall are illustrated in Figure 4; details at the side and rear walls are shown in Figure 5.

The BFR magazine design uses the sliding, single-leaf, chain-operated steel doors, as discussed above. The BFR steel panels are discontinued at the edges of the header and pilasters. The design drawings include details for both the 8-foot an 10-foot doors, allowing the final designer to select the door size depending on the needs of the user.

Earth cover a minimum of 2 feet thick is provided over the roof of the magazine and surrounds the side and rear walls. This cover tapers away from the roof on a 2:1 slope and extends a sufficient distance so that the toe of the earth cover will be at the same elevation as the floor of the magazine. The earth over the magazine roof is sloped slightly from front to back to promote drainage away from the headwall.

NON-STRUCTURAL DESIGN FEATURES

Since the magazine is a semi-buried structure, keeping the inside of the magazine dry is a major concern. This problem is addressed by providing positive drainage of water away from the structure and a waterproofing system.

The standard design includes two options for drainage systems. The first option is a sand-gravel filter system. In this system, a contiguous 6-inch thick layer of sand is placed over the roof and adjacent to the side and rear walls, headwall, and wingwalls. A continuous bed of gravel, at the bottom of the sand fill, drains the water to the foundation drain system. The second option is a drainage composite system. This system uses a drainage mat material with a filter fabric backing, which is placed against the roof, side and rear walls, headwall, and wingwalls. It also drains to the foundation drainage system. The foundation drainage system consists of 6-inch diameter perforated pipes sloped to drain toward the front to the structure and out through the magazine headwall and wingwalls.

Waterproofing is provided to prevent water leakage into the magazine and to prevent corrosion of the buried steel BFR face panels. For the sand-gravel filter drainage system, all buried surfaces are covered with a fluid-applied waterproofing membrane. This membrane is covered with a protection board to prevent damage during backfilling. For the drainage composite system, an elastomeric waterproofing membrane is applied to all buried surfaces. Areas of this membrane that are not covered by the drainage composite are also provided with protection board.

Optional ventilation details for the BFR magazine have been adapted from the U. S. Army 33-15-74 standard magazine. Louvers are provided in the headwall. These louvers are spring-operated with a fusible link in order to close in the event of an exterior fire or explosion. The louvers are shielded with heavy steel plates to prevent fragments from entering the magazine. Also, a duct is provided through the rear wall to a ventilator located above the earth cover. Lighting and lightning protection details have also been adapted from the 33-15-74 standard magazine. Interior and exterior lighting is provided with explosion-proof fixtures. Lighting details accommodate the variable length of the magazine. The lightning protection system meets the requirements of DOD 6055.9-STD.

ADVANTAGES OF THE BFR MAGAZINE

There are numerous advantages in using the BFR magazine instead of other standard magazines. Perhaps the most notable advantage is reduced construction cost. The BFR magazine will be less expensive to build than the standard concrete oval arch magazine or the standard steel arch magazine. Cost comparisons, based on an 80-foot long magazine, are shown in Table 4 below. The most significant savings are in the cost of the structure itself and the cost of the earth cover. Much of the cost savings for the structure itself derives from the ease with which the BFR magazine can be built. Erecting BFR walls is no more difficult than building normal concrete walls, and the BFR face panels become in-place forms, reducing formwork costs. Less conventional reinforcing is needed. Also, the rectangular box shape is significantly easier to build than the concrete arch. The steel arch magazine requires the expertise of a specialty contractor for construction. The earth cover for the steel arch must meet specific density requirements to ensure the arch will perform as designed. The BFR magazine has no such requirements. Because of the BFR magazine's rectangular box shape, the overall earth mound is shorter and requires less fill material. The fill volume of the BFR magazine is about 2100 cubic yards, compared to 3500 cubic yards for both the steel and concrete arch magazines.

Another advantage is in the efficiency of use of the storage volume in the BFR magazine. The BFR magazine provides the same storage volume as the concrete oval arch magazine. However, this space is rectangular, allowing easier stacking of boxes or palettes and permitting the use of shorter stacks. This will make handling stored ammunition and explosives easier.

SUMMARY

The BFR magazine has been shown to be sufficiently strong to resist the effects of an explosion on an adjacent magazine at standard intramagazine distances. The design methods used in this effort included a number of conservative assumptions. Actual performance of the magazine, in the event of an explosion, will certainly be better than predicted by the analysis. The magazine will remain essentially intact and will prevent propagation of the explosion to stored explosives.

As of this writing, the design of the BFR magazine is essentially complete. A standard design package has been prepared. This design package includes detailed drawings showing the BFR structure, foundations, earth cover, doors, waterproofing and drainage systems, lighting, lightning protection, and ventilation systems. It also includes technical specifications, a preliminary cost estimate, and a design narrative. The final package will be incorporated in the U. S. Army library of standard designs as the "Magazine, Steel and Concrete Box, Earth-Covered," standard design 421-80-02. This standard design can be adapted for construction at any site. The site adaptation process will generally include verification of the foundation designs for the specific soil

conditions, producing site, paving and grading plans, and revising the cost estimate and specifications. Site adaptation does not allow changes in the structure other than defining the desired length of the final magazine. This standard design will be maintained by the Huntsville Division, and will be available by inquiring at the address in Reference 19.

The BFR magazine has not yet been approved by DDESB as a standard magazine. Review of this design by DDESB is in progress. We anticipate that DDESB will approve the BFR magazine as a standard magazine.

Table 1: Blast Loads for Feasibility Study

Structural Element	Overpressure (psi)	Impulse (psi-ms)	Duration (ms)
Headwall & Doors	100	1100	22.0
Side and Rear Walls	44.1	1323	60.0
Roof Slab	44.1	1323	60.0

Table 2: BFR Magazine Design Blast Loads

Structural Element	Overpressure (psi)	Impulse (psi-ms)	Duration (ms)
Headwall & Doors (primary load)	100	1100	22.0
Headwall & Doors (secondary load)	200	1100	10.0
Roof Slab	85	850	20
Side Walls	165	900	10.9
Rear Wall	432	1770	8.2

Table 3: Maximum Support Rotations

Structural Element	Maximum Computed Support Rotations (degrees)
Headwall & Doors	4
Door Pilasters	1
Door Header	2
Roof Slab	2
Side Walls	1
Rear Wall	2

Table 4: Standard Magazine Cost Comparison

	Concrete Oval Arch Magazine 33-15-74	Steel Oval Arch Magazine 33-15-73	BFR Magazine
Excavation and Backfill	$ 78,021	$ 77,275	$ 48,650
Structural Work	153,015	126,541	92,576
Doors	19,568	19,568	19,774
Electrical Work	5,547	5,547	5,554
Waterproofing, Painting, Misc. Metal and Other	23,299	23,749	18,970
TOTAL COST	$ 279,450	$ 252,680	$ 183,048

Note: The total cost of the BFR magazine does not include royalties for patent rights. With royalties of 7.5%, total cost becomes $196,770.

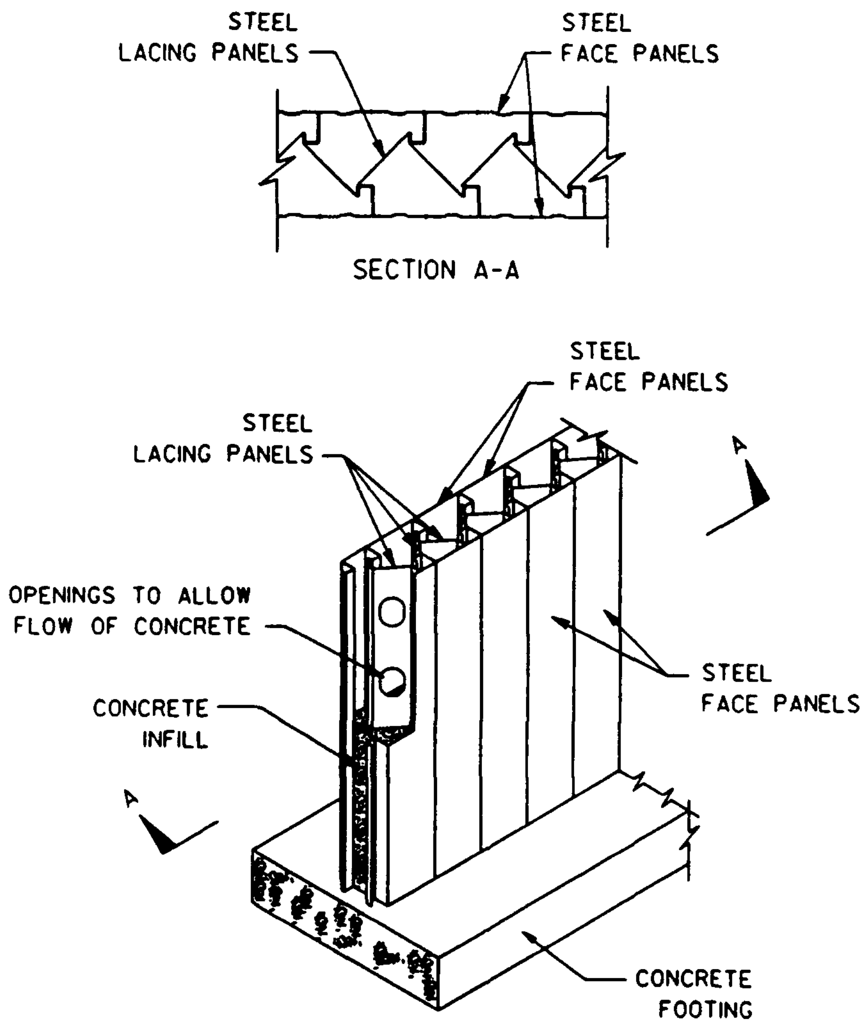

Figure 1: BFR Wall System Details

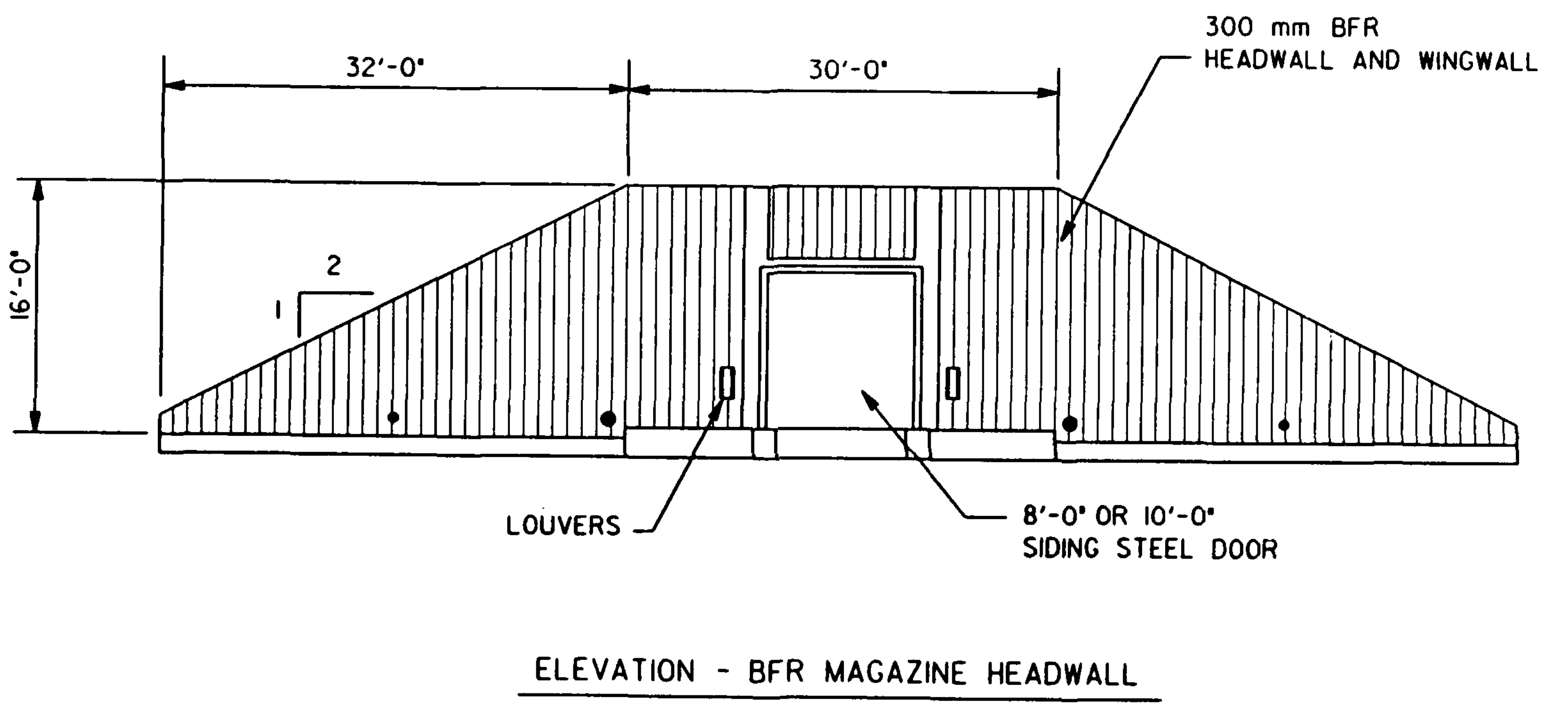

Figure 2: BFR Magazine Exterior Elevation

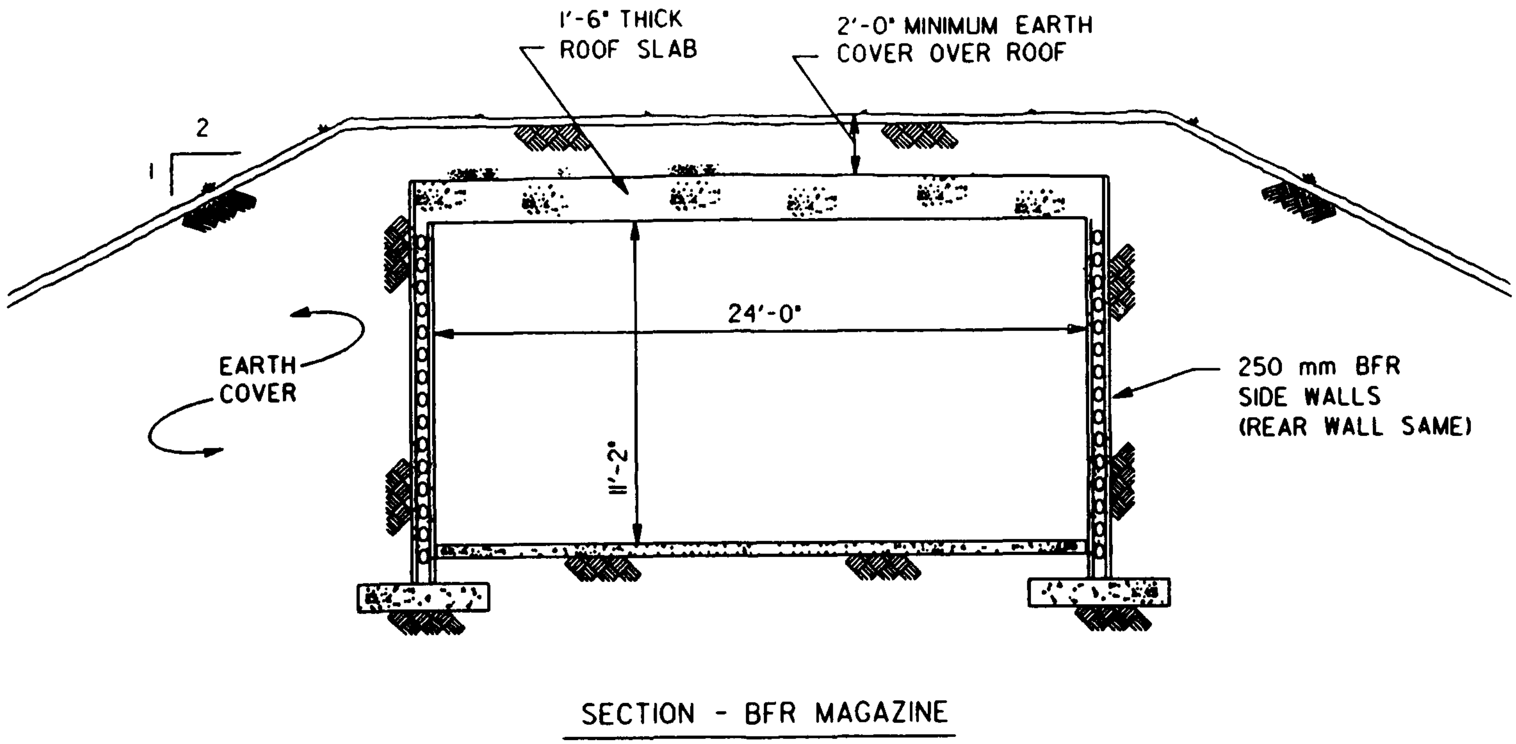

Figure 3: BFR Magazine, Section

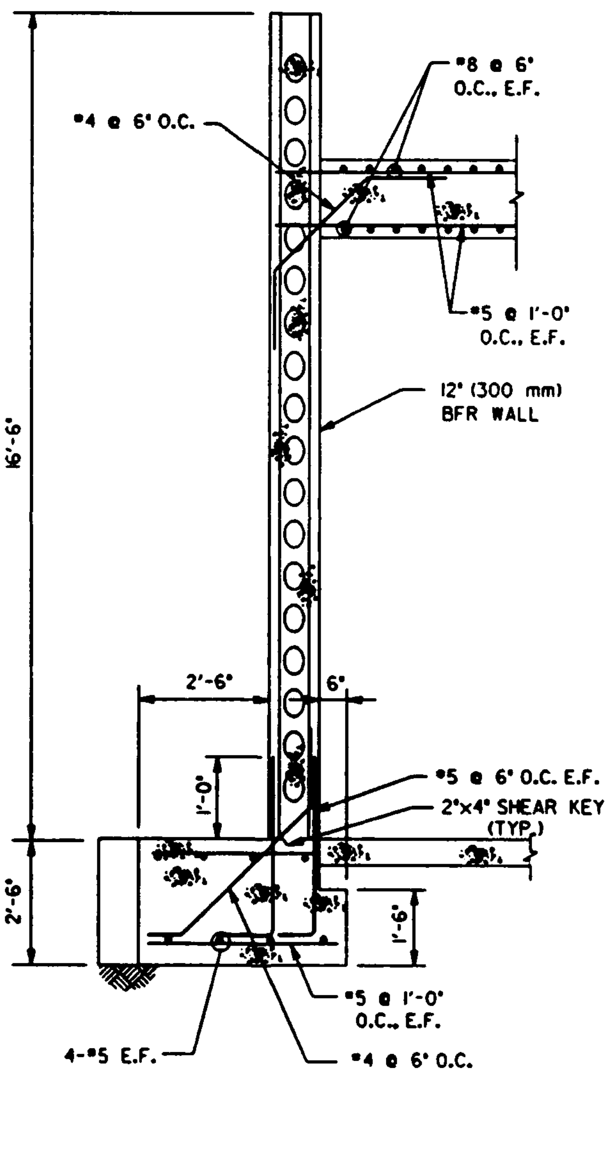

Figure 4: BFR Magazine Headwall Section

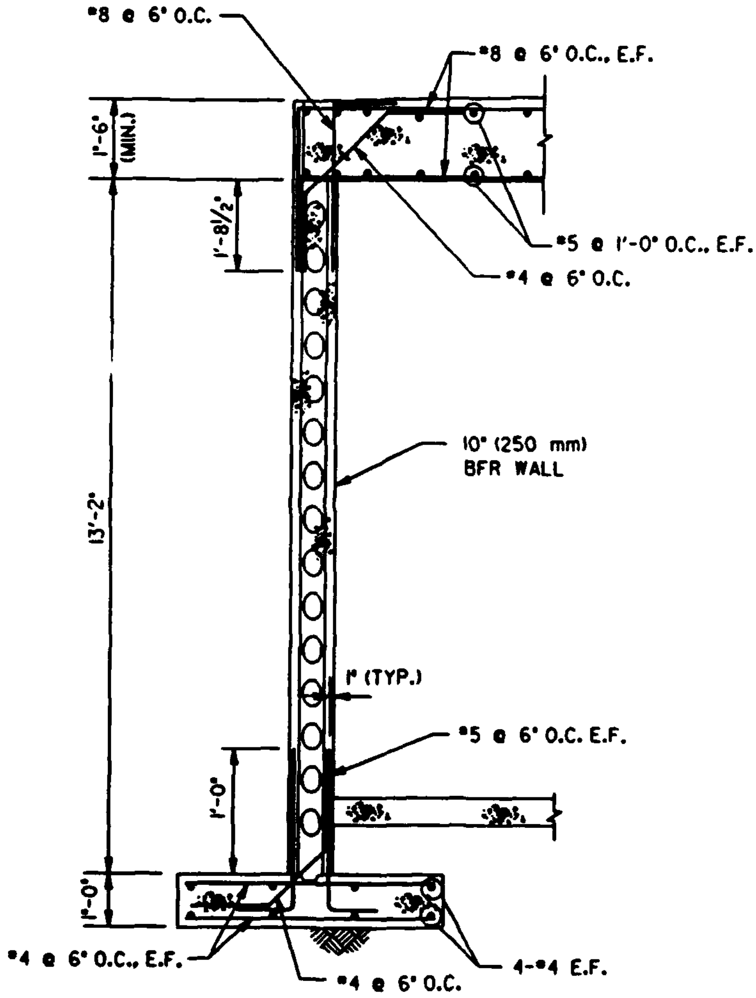

Figure 5: BFR Magazine Side and Rear Wall Section

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SMALL-SCALE HIGH PERFORMANCE MAGAZINE
ROOF AND SOIL COVER FEASIBILITY TEST RESULTS

by

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ABSTRACT

The High Performance (HP) Magazine concept consists of an earth-covered box structure with interior cells where munitions are stored. The cells are designed to prevent sympathetic detonation between cells, thereby limiting the Maximum Credible Event (MCE) to the Net Explosive Weight (NEW) stored in any cell. The reinforced concrete box structure and soil cover are designed to limit the safe distance for the MCE from blast, fragment, and debris outside the magazine.

Small-scale (1/10) feasibility tests were conducted by the Terminal Effects Research & Analysis (TERA) Group at Socorro, NM in 1991. Results from these tests will be used to demonstrate the feasibility of the HP Magazine roof and soil cover to mitigate external debris and pressure hazards. A reusable magazine test fixture was built and six tests were performed in which 2.4 in. thick reinforced concrete roof specimens were covered with 0, 3.6, and 7.2 in. of soil. The explosive test charges were 7.43-lb rectangular blocks of Composition C4 (equivalent to 10 lb of TNT). Data included airblast instrumentation, high-speed motion pictures, and debris recovery.

The test results demonstrated the feasibility of the HP Magazine roof and soil cover to mitigate external debris and pressure hazards. For a full-scale 10,000-lb MCE, the safe ESQD (Explosive Safety Quantity Distance) pressure arc was reduced to about 500 ft (23.2 $W^{1/3}$), the distance from the magazine that the peak pressure decays to 1.2 psi. The full-scale ESQD arcs for debris were reduced to about 800 ft (37.1 $W^{1/3}$) and 550 ft (25.5 $W^{1/3}$) for soil covers of 3 and 6 ft, respectively. This is much less than the NAVSEA OP-5 (Reference 1) ESQD arc for debris and fragment which is 1,250 ft.

INTRODUCTION

Background

A new storage magazine is needed by the Navy to solve munitions storage problems. Existing magazines encumber large land areas to meet ESQD requirements of NAVSEA OP-5. NCEL is currently investigating the feasibility of a new magazine (Reference 2) that will reduce the land area encumbered by ESQD arcs and improve the efficiency of weapons handling operations. This new HP Magazine concept would reduce

encumbered land by 80% (or increase storage density on existing land by a factor of up to 8 times) and significantly reduce operational costs. Reduction of encumbered land is achieved by reducing the Maximum Credible Event (MCE) in the magazine to 10,000 lb Net Explosive Weight (NEW) of High Explosive (HE) by using cells with walls that prevent sympathetic detonation (SD). The magazine would be designed to store about 200,000 lb (NEW) of palletized ordnance (e.g., bombs, bullets, projectiles, torpedoes) or about 60,000 lb of containerized missiles. However the ESQD arcs would be based on an MCE of only 10,000 lb (the NEW in one cell).

The safe ESQDs are given in Reference 1. The pressure ESQD arc for an MCE of 10,000 lb is 862 ft ($40W^{1/3}$, the distance from the magazine that the peak pressure decays to 1.2 psi). This is much less than the OP-5 ESQD arc for debris and fragments which is 1250 ft (the distance at which the hazardous debris density is 1 per 600 ft^2). The debris and fragment safe distance must be reduced in order to take full advantage of the low MCE.

The HP Magazine concept includes a reinforced concrete roof and added soil cover to mitigate the fragment and debris hazard. The roof and soil cover will stop high velocity primary weapon fragments. The reinforced concrete roof will use close flexural steel spacing and shear stirrups to reduce the area of breaching. Deeper than normal soil cover (> the 2 ft used on standard earth covered magazines) will mitigate the roof debris hazard.

This roof design provides more containment of the blast wave than standard earth covered magazines. Exits are short tunnels which will choke the exit pressures, reduce the safe pressure distance in most directions, and reduce the total encumbered land area. However, the tunnel exits (which focus the blast wave) can also increase the safe pressure distance on the axis of the tunnel.

Objectives

Accurate methods do not exist for determining the HP Magazine internal and external loads, roof/soil cover breakup, and safe debris distance. Testing is necessary to improve and verify existing methods and to develop new analytical methods. Small-scale tests are required to inexpensively determine the effect of the many variables that effect the performance of the HP Magazine roof. The small-scale parameter tests will be used to verify the applicability of the existing analytical methods, and to provide data to improve the methods for the specific geometry of the HP Magazine. The small-scale tests are also necessary to show the feasibility of the concept for limiting safe hazard distances to about $40W^{1/3}$.

The objective of this test program is to determine the effect of roof & soil cover design parameters on safe debris and pressure distances.

The specific objectives are to:

- Determine the effect of soil cover depth, roof span and support type (center span full height wall vs. column support), tunnel exit conditions, charge density (W/V), and donor location on debris density vs. range.

- Determine the effect of tunnel exit conditions (area, number, and location) and W/V on external pressure vs. range and azimuth.

- Determine the breakup pattern and debris characteristics (launch velocity & angle, mass, and shape factor) of the roof and soil cover for use in verifying and improving analytical procedures.

Scope

Scale model testing (scale factor, $F_s = 1/10$) will be used to determine the effect of the key variables on safe debris range (scaled distance at which the debris density = 1 hazardous fragment per 600 ft^2) and safe pressure range (scaled distance at which the peak incident pressure = 1.2 psi). Geometric scaling (model dimensions = F_s * full-scale dimensions) will be used to properly scale most key parameters (gravity being the important exception). Geometric scaling (especially at the relatively large scale of 1/10) has been shown to be accurate for modeling the pressure environment. NEW scales as F_s^3. The scale model tests should also provide accurate debris launch angles and velocities. However, accurate prediction of full-scale debris mass, debris range, and roof breakup, will require test results from at least two scale model sizes. Analytical and empirical procedures will be used to convert the small-scale debris mass and distance results to predictions of full-scale response.

The key variables to be investigated are charge density (W/V), roof & soil weight, roof span length between walls, and roof edge conditions (free vs restrained). The scope of the test program is outlined in Table 1. The following parameters were held constant for all six tests:

- NEW = 10 lb TNT equivalent (W = 7.43 lb of Comp C-4 for Tests 1-5, and W = 7.35 lb of Comp C-4 for Test 6)

- Charge located in center cell of magazine

- One open tunnel exit at each end

The edges of the roof slabs were free to move upward in Tests 1-3, but were restrained in Tests 4-6. Soil cover depths of 0, 3.6, and 7.2 inches were used in the six tests. Test 6 used a half-width magazine (larger W/V ratio) to obtain higher reflected shock and gas pressure loads.

TEST SETUP

Test Site

The tests were conducted in the West Valley area of the Terminal Effects Research and Analysis Group (TERA) Field Laboratory located at the New Mexico Institute of Mining and Technology (NMIMT) in Socorro, New Mexico. The site dimensions are shown in Figure 1. The outside boundaries were determined from the debris recovery and pressure gauge

line requirements. Debris recovery areas and pressure gauge lines are also shown in Figure 1. The area was re-bladed and re-rolled prior to the test program. The test site was cleared of most debris between each test.

Test Fixture

A reusable magazine test fixture (with replaceable cell walls and center span roof supports) was provided to conduct the 1/10-scale tests of HP Magazine roof specimens (see Figure 2). The reusable fixture consists of 4-ft thick by 4-ft high (outside dimension) reinforced concrete walls poured monolithically with a 2'-6" thick reinforced concrete floor. The inside of the walls were lined with 3/8-in. thick steel plate. The fixture was designed as a partial containment cubical with venting through the open tunnel exits and the frangible roof and soil cover. The blast loads acting on the inside faces of the walls were resisted by transfering the loads into the floor which was heavily reinforced with two horizontal layers of #6 "tension" bars spaced @ 10 in. in each direction. Each end of these continuous "tension" bars was bent 90^{o} upward into the wall. To help transfer the load downward into the floor, #6 vertical bars spaced at 10 in. were located near the inside face of the four walls and crossed through the potential horizontal shear crack. The test fixture was also strengthened by placing three #6 flexural bars in each face of the four walls. These flexural rebars were tied together with #4 closed-ties spaced at 18 in. No diagonal rebars were used at any of the sidewall/endwall, sidewall/floor, or endwall/floor corners. The top of the fixture was flat to simply support a 3-in. wide roof slab bearing surface. 1-in. diameter embedded hook bolts were spaced at 12 in. to provide translational/rotational edge restraint in the slab for Tests 3 through 6. Each end wall has two 16-in. diameter circular exits. However, for all six tests, a 3/4-in. thick steel plate closed off one exit in each end wall.

Directly under the donor explosive, a 9-in. x 12-in. rectangular cavity was formed in the floor. This cavity was partially filled with sand and then a 3-in. thick steel plate was placed flush with the surrounding concrete floor to mitigate cratering and provide a reflecting surface.

The roof in Tests 1 through 5 was supported by a continuous 2x4 wood beam resting on 4x4 (column) wood supports to the floor. Test 6 setup required a full-height sand-filled wooden wall center support. The 19-in. by 19-in. donor cell (inside dimensions) was simulated with 3-in. thick x 9.5-in. high unreinforced concrete walls (Figure 2). A photograph of the completed test fixture at TERA is shown in Figure 3.

Roof Specimens

The reinforced concrete roof slabs were built as shown in Figure 4. The test plan called for a concrete mix proportioned for a 28-day compressive strength of 4,000 psi. However, due to expected time schedule constraints, a high-early strength concrete mix was chosen to obtain the strength in 14 days. Figure 5 shows the distribution of the

fine and coarse aggregate used in the following mix:

0.60/1.0/1.30/2.28

These numbers denote relative weights of water, cement, fine and coarse aggregate. Each slab was tinted with a different colored admixture to facilitate debris analysis. For some unknown reason, the strength results of concrete test cylinders cast during the pouring of the six roof slabs were consistently less (13-37%) than 4,000 psi.

The reinforcing steel in the 6'-6" by 6'-6" area directly above the donor explosive (as shown in Figure 4) modeled the flexural and shear steel in a full-scale static design for a roof with 4 ft of soil cover. To reduce cost, the concrete x-section "B" away from the donor charge did not include the shear stirrups. These areas of the slab were not expected to breach and therefore the shear steel requirements were relaxed. The flexural strength in these areas was unchanged. In the full-scale design, the required main flexural steel is as follows:

Grade 60, #9 rebar	
Static design yield stress, f_s	66,00 psi
Bar diameter, d	1.128 in.
Bar area, A	1.0 $in.^2$
Bar spacing, s	10 in.
Distance between centroids of compr. & tens. rebar, d_c	19.1 in.

Ideally, the model reinforcement should be made of the same material with the following 1/10-scale properties:

Bar diameter, d	0.113 in.
Bar area, A	0.010 $in.^2$
Bar spacing, s	1.0 in.
Distance between centroids of compr. & tens. rebar, d_c	1.91 in.

In designing the model structure, compromises were made in rebar strength, size and spacing to reduce costs and simplify construction, while keeping the moment capacity (i.e., $A f_s d/s$) approximately unchanged. The final model main reinforcement selected was a carbon steel, welded wire cloth with the following properties:

Static yield stress, f_s	86,636 psi
Bar diameter, d	0.120 in.
Bar area, A	0.0113 $in.^2$
Bar spacing, s	1.12 in.
Distance between centroids of compr. & tens. rebar, d_c	1.85 in.

The model shear reinforcing was double leg stirrups made from 20 gauge 60 ksi wire (which corresponded to single leg #4 stirrups at full-scale).

Soil Cover

The soil cover used in all tests was uncompacted dry sand. A uniform density of 107.5 pcf was consistently achieved by simply dropping the sand from a skip loader onto the roof slabs. A photograph of a roof slab with soil cover just prior to testing is shown in Figure 6.

Explosive Donor

Rectangular Composition C4 explosive charges were constructed to simulate (1/10-scale) the full-scale magazine MCE of 10,000 lb TNT. The Net Explosive Weight (NEW) for each test was 10.0 lb TNT equivalent, based on gas pressure equivalency. The weight of Composition C4 required to produce the same peak gas pressure as 10.0 lb of TNT was determined from Reference 3 and is shown below:

Test No.	W (lb)	Height (in.)	Width (in.)	Length (in.)
1-5	7.43	4	5	6.3
6	7.35	4	5	6.2

The TNT equivalencies for the C4 are 1.35 for Tests 1-5 and 1.36 for Test 6. The bottom of the explosive charge was located 2.2 inches off the steel floor plate.

Data Requirements

Airblast. The airblast instrumentation consisted of 23 gauge stations: nineteen stations external to the test fixture and four stations internal to the test fixture. Piezo-resistive pressure transducers were used at all stations except the two piezo-electric PCB transducers used at Stations SP-1 and SP-2. The signals from the transducers were recorded on magnetic tape by Honeywell Model 101 14-track FM tape recorders operating at 120 ips. The system bandwidth was 80-kHz. A programmable sequence-control timer detonated the charge and operated the recording system. The data for each test were later digitized, processed, and plotted.

The external pressure gauges were surface mounted to measure incident blast overpressures along gauge lines to the front ('F'), on a diagonal ('D'), to the side opposite the center of the test fixture ('S'), and to the back ('B'). External pressure gauge locations are shown in Figure 7.

The internal pressure gauges were located inside the test fixture to measure the shock and gas overpressures. Two of the gauges measured the internal shock overpressures just inside the front and back tunnel exits at the cylinder bottoms. The other two gauges were located in opposite long walls of the test fixture to measure the gas pressure

inside the fixture. The gauge was thread-mounted at mid-height of the wall so the gauge diaphragm was flush with the face of the wall. A perforated steel filter was placed over the diaphragm to protect it from internal debris and attenuate the shock pressures. The internal pressure gauge locations are also shown in Figure 7.

Photographic Coverage. Five high-speed motion picture cameras and one real-time video camera were used in each test. The high-speed cameras (Nos. 1 through 5) were used to measure initial debris angle and velocity. The real-time camera (No. 6) was used to cover the overall event. Camera locations are shown in Figure 8.

Debris Recovery. Debris was recovered and characterized by TERA. The debris recovery zones were two 5-degree sectors to the front and side of the test fixture, as shown in Figure 9. The recovery sector to the side began at 40 ft from the inside wall of the test fixture and extended to 460 ft. The recovery sector to the front began at 41-3/4 ft from the inside wall of the test fixture and extended to 241-3/4 ft. A concrete pad was used in the first 200 ft of each 5-degree sector. The debris recovery zones were formed by the 5-degree boundaries and radii at 20-ft spacings. All debris was collected in the recovery zones. Debris passing through a 3.35 mm sieve was not analyzed. A sieve analysis (using 4.75mm and 6.35 mm sieves) was run on debris retained by the 3.35 mm sieve but passed by a 9.50 mm sieve. The debris retained by the 3.35 mm sieve was counted and collectively weighed. The debris retained by the 4.75 mm and 6.35 mm sieves was counted and individually weighed. The debris retained by the 9.5 mm sieve was individually weighed, and measured (length, width, and thickness).

Individual debris outside the recovery zones was mapped by TERA. About 50 pieces of the largest debris and at the greatest distances were recovered for each test. This debris was categorized by size as described above for the debris retained by a 9.50 mm sieve.

TEST RESULTS

Reference 4 contains the digitized data for the internal and external pressure gauges of all six tests. Impulses were obtained by numerically integrating the digitized pressure data. No filtering of the data was employed. The data for each test are referenced to a common zero time (Time of Detonation) and are displayed with time in milliseconds as the abscissa. A typical data record is shown in Figure 10. The values of the measured peak pressures in all six tests are listed in Table 2.

Reference 4 also contains the complete records of the debris collected from all six tests.

High speed films showing test results are in the possession of NCEL.

Observed Structural Response/Breakup

Review of the videos/high-speed films combined with visual studies of the condition of the tested roof slabs produced the following general observations:

- The roof slabs in all six tests were lifted off the test fixture as a rigid body and propelled straight upward. The maximum vertical lift occurred in Test 1 (no soil cover) and the minimum occurred in Tests 3, 5 and 6 (7.2 inches soil cover).

- The final resting positions for all six tests were within the boundaries of the test fixture.

- Breaching of the roof slabs occurred directly above the location of the explosive charge in all six tests. The amount of breaching was inversely proportional to the soil cover depth.

Photographs of the six tested slabs are contained in Figures 11 through 20.

Pressure Data Analyses

The pressure outside the test fixture consists of two components: (1) directional leakage pressure from the tunnel exits and (2) leakage pressure through the breached roof and soil cover. A detailed explanation of the methods developed to calculate the pressures from these two physical phenomena are contained in Reference 4.

The method used to calculate the external pressure from the tunnel exits was recently developed by the U.S. Army Ballistics Research Laboratory (Reference 5). The following relationship is applicable for magazines with one tunnel exit:

$$p_o = 1.733[d(W/V)^b]^{0.83}(A_t/A_c)^{0.19}[R_o/(1.173\ D)]^{-1.35} \qquad (1)$$

where,

p_o = peak pressure at distance R_o, psi

R_o = distance from opening along centerline axis (0^o line), ft

W = explosive storage weight, lb

V = total volume of chamber (test fixture) and tunnels, ft^3

for $W/V \le 0.025$,	$d = 4000$ $b = 0.82$
for $0.025 < W/V < 0.07$,	$d = 945$ $b = 0.43$
for $W/V \ge 0.07$,	$d = 2675$ $b = 0.82$

A_t = cross-sectional area of the tunnel opening, ft^2

A_c = cross-sectional area of the chamber (test fixture), ft^2

D = equivalent circular cross-sectional diameter of tunnel, ft

This equation is partially based on the following two equations for peak gas pressure inside the chamber (p_c) and peak pressure at tunnel exit (p_x):

$$p_c = d(W/V)^b \tag{2}$$

$$p_x = 1.733(P_c)^{0.83}(A_t/A_c)^{0.19} \tag{3}$$

The equation for p_o along any line "a" degrees from the 0^o line is given as:

$$p_o = 1.733[d(W/V)^b]^{0.83}(A_t/A_c)^{0.19}[R_a/(1.173\ D\ F_a)]^{-1.35} \tag{4}$$

where,

R_a = distance from opening along "a" line, ft

F_a = $[1 + (a/56)^2]^{-0.741}$

Exit pressures for multiple tunnels (2) were calculated, at a given range and azimuth, by conservatively adding the peak pressures calculated from Equation 4 for each tunnel exit.

The method used to calculate the external pressure from the leakage through the breached roof and soil cover is based on procedures (Reference 6) developed by the U.S. Army Waterways Experiment Station (WES). The following relationship is for fully-coupled buried charges (explosive charge in direct contact with soil cover):

$$p_o = 3.51\ (h/W^{1/3})^{-2.7}\ (R/W^{1/3})^{-1.06} \tag{5}$$

where,

p_o = peak pressure at distance R, psi

h = cover depth, ft

R = horizontal distance from explosive source, ft

W = explosive weight, lb

However, our tests were considered as decoupled buried charges (air gap between charge and soil cover). WES has determined the following coupling factor (C_{cf}) to relate fully-coupled and decoupled buried charges:

$$C_{cf} = 0.03358\ (W/V)^{0.4555}$$

where,

W = decoupled explosive weight, kg

V = total chamber volume, m^3

The equivalent fully-coupled charge weight is:

$$W_{cf} = C_{cf} W$$

Calculation of W_{cf} allows the use of the relationship (Equation 5) developed for fully-coupled charge weights.

The predicted peak gas and tunnel exit pressures were calculated from Equations 2 and 3 and listed below:

Pressure Measurement	Peak Pressure (psi) for Test No,	
	1 - 5	6
Gas Pressure, p_c	287.1	460.6
Exit Pressure, p_x	133.4	225.3

The gas pressure data (GP gauges) was very poor and not usable. The tunnel exit pressure data (SP gauges) was much better in providing values of peak pressure and duration. Apparently, the environment inside the test fixture (shock, temperature, and debris) was too severe for the GP gauges. For the next Phase II test series, the protection of the GP gauge diaphragm will be enhanced. Statistically, the average and standard deviation of the peak exit pressures are listed below:

Quantity	Test Nos. 2 - 5	Test No. 6
Average Pressure, psi	399	432
Standard Deviation, psi	60	33

These values are much greater than predicted.

The predicted peak external pressures from the two methods were calculated in Reference 4 for all six tests. Although the peak pressures from these two components will occur at different times, they were added to obtain the conservative test predictions listed in Table 3. Because all six tests had a front and back tunnel, the predicted pressures to the front and back are identical. As an example, the predicted pressures for Test 3 are plotted versus range in Figure 21 for the four directions (i.e., front, diagonal, side, and back). As a means of reference, the peak pressure from a hemispherical surface burst (Reference 7) is also shown on this figure. The measured external peak pressures for Test 3 listed in Table 2 are also plotted in Figure 21. The test data for each test are very similar and always less than the surface burst curve. Except for Test 1 (no soil cover), the close-in pressures to the side of the test fixture were greatly reduced. Apparently, the absence of a soil cover allowed a significant amount of pressure to vent through the breached concrete roof immediately above the explosive charge and reach the nearby side pressure gauges. For Test 1, the measured peak pressures to the front, back, and diagonal were less than predicted, while the pressures to the side were greater than predicted. Good agreement of the measured and predicted peak pressures occured for Tests 2 through 5. For Test 6, the measured peak pressures were greater than predicted. Better agreement would have occured if the full volume of the test fixture, and not the half volume, was used in the prediction modeling. Apparently, the 3-1/2 in. thick sand-filled full-height center wall was breached immediately after detonation and thus the actual test setup modeled a full-volume test fixture.

Debris Data Analyses

Debris Outside Recovery Sectors. Analyses of the debris collected outside the recovery sectors indicate that the maximum debris distance is reduced by increasing the soil cover depth. This trend is shown in Figure 22 for Tests 4 (3.6 in. soil cover) and 5 (7.2 in. soil cover).

Debris Within Recovery Sectors. An example of the debris areal distribution by zone is shown in Table 4 for the side recovery sector of Test 1. This table contains all debris with mass greater or equal to the critical mass* of 0.000375 lb (2.6 grains). This 1/10-scale debris data was scaled up by applying the trajectory relationship between a 1/10-scale debris and full-scale debris. This relationship is graphically shown in Figure 23 and is valid for a 1/10-scale mass of 0.038 lb (average mass of debris collected in the large debris mapping area) at an initial angle of 40° above the horizontal. The full-scale debris areal number density, calculated as the cumulative number of debris per 600 ft^2, is listed in this table and shown in Figure 24. The debris densities for all six tests to the side and front directions are shown in Figures 24 and 25, respectively. The debris hazard range is defined to be that range beyond which the areal number density of hazardous fragment is one per 600 ft^2 or below. The hazardous range for

* Trajectory (Reference 8) calculations found that critical debris with a mass of 0.000375 lb or larger are hazardous (58 ft-lb) upon impact.

all six tests were graphically obtained from the above figures and are listed in Table 5 and plotted in Figures 26 and 27 versus full-scale soil cover depth. Also shown in these figures are the safe debris ranges predicted by the "Building Debris Hazard Prediction Model, DISPRE" (Reference 9).

CONCLUSIONS

The measured safe pressure distances (i.e., distance from the test fixture exterior that the peak pressure decays to 1.2 psi) to the front, diagonal, and side directions for all six 1/10-scale tests are listed in Table 6. Neglecting Test 1 and the side direction of Test 5, the safe distances varied from 41.8 to 50.8 ft. The corresponding safe pressure distances for a full-scale HP Magazine would vary from 418 to 508 ft. This is still less than the 862 ft (40 $W^{1/3}$) required by Reference 1 for an MCE of 10,000 lb NEW.

The external pressures predicted by the methods outlined in this paper compared very well with the measured pressures to the front, diagonal, and back directions. Their use in predicting the safe pressure distances in these directions would be conservative. However, comparisons of the predicted and measured pressures to the side were not as good. Their use in predicting the safe pressure distance in the side direction would be unconservative. At peak pressures less than about 1.2 psi, the measured peak pressure to the side vs. range curves for the five tests with soil cover (i.e., Tests 2 - 6) are very close to the curves for the front direction. Therefore, it is recommended that the safe pressure distance to the side be set equal to the safe distance to the front. The configuration of future Phase II small-scale tests will change from two tunnel exits (i.e., one at each end) to one tunnel exit. Phase II test results may result in changes to prediction methods recommended in this report.

The full-scale safe debris distances based on the worse-case measured 1/10-scale test data listed in Table 5 are shown below:

Full-Scale Soil Cover, h_s (ft)	Full-Scale Safe Debris Distance, (ft)
0	891
3	800
6	542

These values are all less than the 1,250 ft required by Reference 1.

It is concluded that the HP Magazine concept can mitigate the fragment and debris hazard and that the required safe pressure and debris hazard ranges will significantly reduce the total area encumbered by ESQD arcs.

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8. Naval Surface Warfare Center. Technical Paper: TRAJ -- A Two Dimensional Trajectory Program For Personal Computers, by Paul E. Montanaro. Published in Seminar Proceedings, 24th DDESB Seminar, St. Louis, MO, Aug 1990.

9. Southwest Research Institute. Technical Report: Building Debris Hazard Prediction Model, by Patricia M. Bowles, Charles J. Oswald and Luis M. Vargas. San Antonio, TX, Feb 1991.

Table 1. Schedule of Tests.

Test No.	Charge Weight[1] of Comp C-4, W (lb)	Roof/Soil Cover Configuration	Roof[2] Weight (psf)	Volume	Roof Edge Conditions
1	7.43	2.4" roof	30	Full	Free
2	7.43	2.4" roof + 3.6" soil	63	Full	Free
3	7.43	2.4" roof + 7.2" soil	96	Full	Free
4	7.43	2.4" roof + 3.6" soil	63	Full	Restrained
5	7.43	2.4" roof + 7.2" soil	96	Full	Restrained
6	7.35	2.4" roof + 7.2" soil	96	1/2	Restrained

[1] The Net Explosive Weight (NEW) for each test is 10.0 lb TNT equivalent, based on gas pressure equivalence

[2] Roof density = 150 pcf; soil density = 110 pcf

Notes:

- Both exits at each end are 16" diameter (Area = 201 in^2)
- Test fixture volume = 148.5 ft^3 in Tests 1-5
- Test fixture volume = 74.25 ft^3 in Test 6

Table 2. Measured Peak Pressures

Gauge No.	Peak Pressure (psi) for Test No,					
	1	2	3	4	5	6
SP-1	308.1	339.9	432.2	430.0	449.7	454.9
SP-2	395.4	327.2	470.5	320.4	418.6	407.7
GP-1	332.0	234.2	-----	274.2	293.6	-----
GP-2	565.9	357.8	-----	360.8	609.1	-----
F-1	----	4.48	4.90	4.55	4.47	5.00*
F-2	2.06	2.25	2.40	1.92	2.33	2.45
F-3	1.52	1.55	1.67	1.47	1.61	----
F-4	0.84	0.88	0.90	0.82	0.71	0.87
F-5	----	0.67	0.62*	0.69	0.55	0.60*
F-6	0.40*	----	----	0.47	0.40	0.42
F-7	0.22	0.25	0.25*	0.30*	0.25	0.23
D-1	1.30	1.39	1.56	1.28	1.37	1.49
D-2	0.79	0.86	0.97	0.80	0.84	0.97
D-3	0.54	0.57	0.67	0.63	0.58	0.66
D-4	0.37	0.45	0.48	0.47	0.42	0.47
S-1	8.89	1.57	1.80	1.64	1.63	1.87
S-2	6.52	1.15	----	1.32	1.33	1.46
S-3	3.86	1.38	1.23	1.16	1.12	1.33
S-4	1.54	1.22	1.24	1.24	1.12	1.43
S-5	0.95	0.50	0.49	0.54	0.54	0.72
B-1	0.93	1.05	0.90	0.79	0.77	1.00
B-2	0.44	0.52	0.43	0.44	0.48	0.49
B-3	0.25	0.30	0.28	0.25	0.28	0.29

* Adjusted for zero shifts or excessive spike

Table 3. Predicted Peak External Pressures

Location		Peak Pressure (psi) for Test No,			
Azimuth (Degree)	Range (ft)	1	2 & 4	3 & 5	6
Front (0)	20	5.59	4.56	4.46	7.51
	30	3.38	2.67	2.60	4.39
	40	2.38	1.84	1.79	3.00
	55	1.60	1.21	1.17	1.97
	75	1.09	0.80	0.77	1.30
	100	0.77	0.55	0.53	0.88
	150	0.46	0.32	0.31	0.52
Diagonal (30)	40	2.03	1.48	1.43	2.41
	55	1.39	0.99	0.95	1.60
	75	0.96	0.66	0.63	1.06
	100	0.67	0.45	0.43	0.73
Side (90)	15	3.44	1.66	1.48	2.50
	20	2.68	1.39	1.26	2.13
	30	1.83	1.00	0.92	1.56
	50	1.09	0.61	0.56	0.93
	75	0.70	0.39	0.35	0.60
Back (180)	55	1.60	1.21	1.17	1.97
	100	0.77	0.55	0.53	0.88
	150	0.46	0.32	0.31	0.52

Table 4. Debris Density in Side Recovery Sector for Test 1.

Zone Nomenclature	1/10 - Scale			Full-Scale		
	Range,[1] R_z (ft)	Number Debris, N	Cumulative Number Debris, N_T	Range,[2] R_z (ft)	Area,[3] A_z (ft^2)	Debris Density (#/600 sf)
S21	460	0	0	2829.0	52,811	0.00
S20	440	1	1	2609.0	49,344	0.01
S19	420	0	1	2385.0	44,710	0.01
S18	400	1	2	2163.2	37,130	0.03
S17	380	1	[illegible]	1959.9	35,015	0.05
S16	360	3	6	1747.0	28,501	0.13
S15	340	3	9	1552.7	24,159	0.22
S14	320	2	11	1367.0	19,819	0.33
S13	300	3	14	1193.8	15,990	0.53
S12	280	2	16	1033.7	12,622	0.76
S11	260	1	17	887.8	10,119	1.01
S10	240	4	21	751.4	8,127	1.55
S9	220	8	29	632.3	6,558	2.65
S8	200	14	43	518.9	3,863	6.68
S7	180	30	73	438.3	3,300	13.27
S6	160	29	102	357.6	2,670	22.92
S5	140	25	127	278.7	1,270	60.00
S4	120	67	194	231.6	1,076	108.18
S3	100	120	314	184.5	882	213.61
S2	80	130	444	137.4	688	387.21
S1	60	115	559	90.3	313	1,071.57

[1] Distance from roof edge to outside edge of zone

[2] Obtained from Figure 37

[3] $A_z = 2 \tan 2.5^\circ (R_z - R_{z-1})(R_z + 30)$; for Zones S1 thru S10

$A_z = 2 \tan 2.5^\circ (R_z - R_{z-1})[(R_z + R_{z-1} + 60)/2]$; for Zones S11 thru S21

Table 5. Full-Scale Safe Debris Distances

Test No.	Measured Safe Debris Distance (ft) to,		Predicted Safe* Debris Distance (ft)
	Side	Front	
1	891	718	1,050
2	323	661	599
3	133	542	436
4	800	661	599
5	239	506	436
6	236	218	436

* From "DISPRE"

Table 6. Measured 1/10-Scale Safe Pressure Distances*

Azimuth	Safe Distance (ft) for Test No,					
	1	2	3	4	5	6
Front	45.4	46.2	47.4	44.7	44.8	45.6
Diagonal	42.1	44.1	47.7	41.8	43.6	47.0
Side	57.0	45.7	46.0	46.1	20.8	50.8

* Distance from the exterior of the test fixture that the peak pressure decays to 1.2 psi.

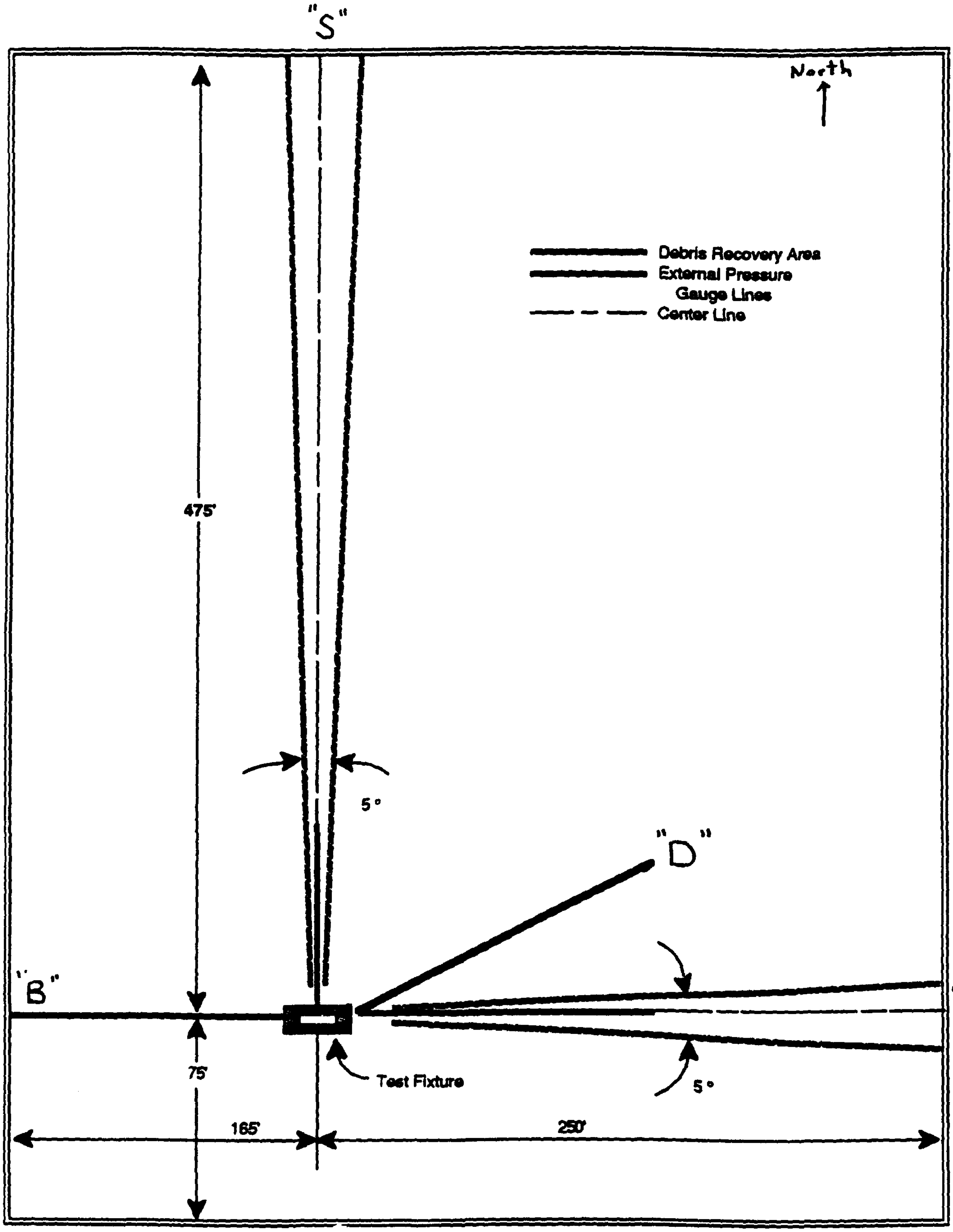


Figure 1. Overall site dimensions.

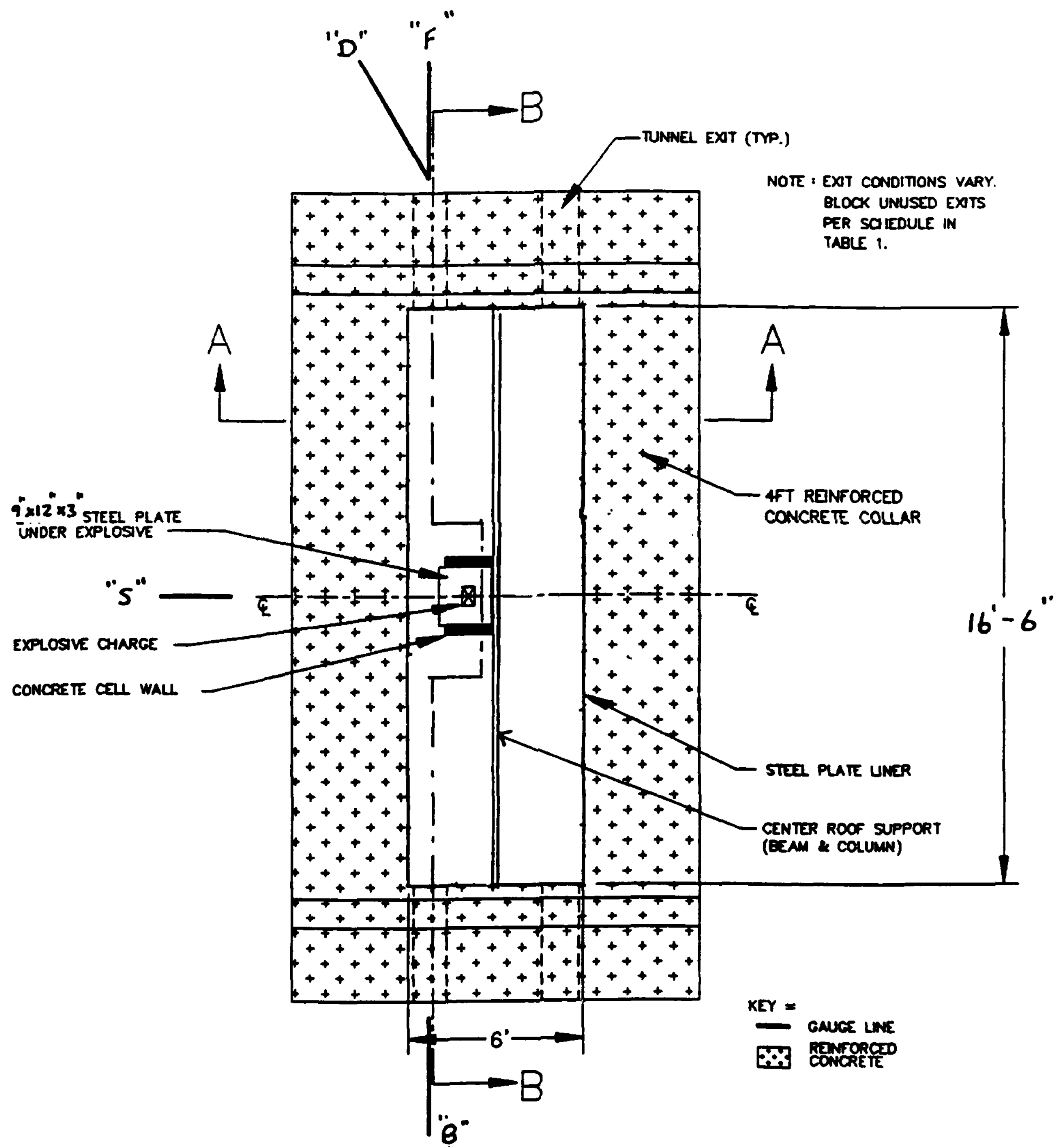


FIGURE 2a. TEST FIXTURE : PLAN VIEW (ROOF NOT SHOWN)

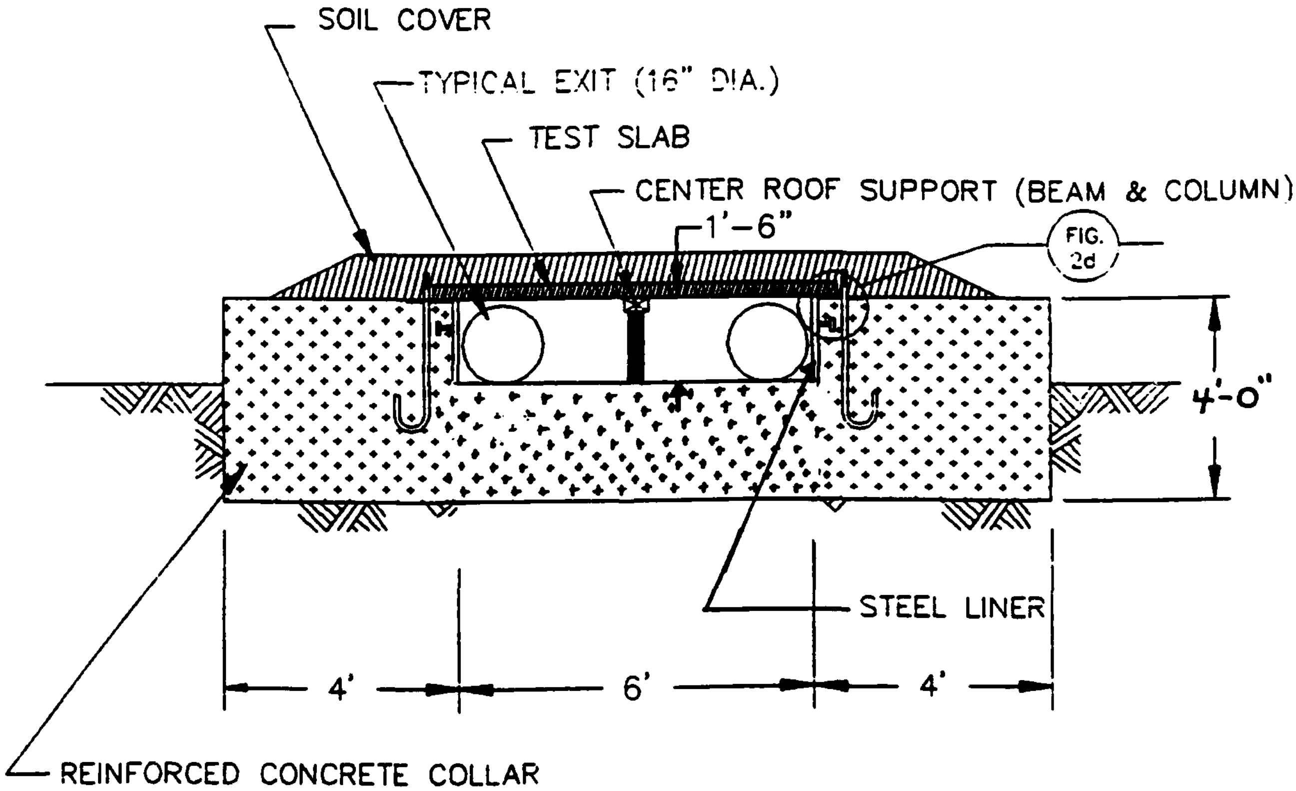


FIGURE 2b. TEST FIXTURE : SECTION A-A

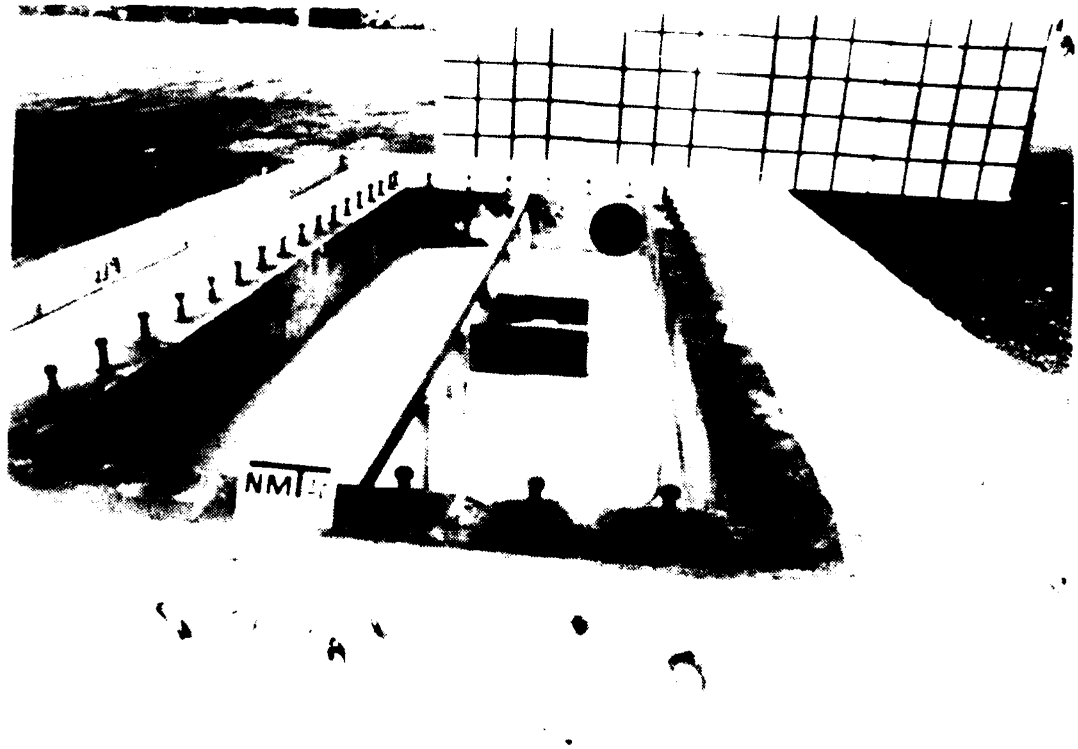


Figure 3. Test fixture interior.

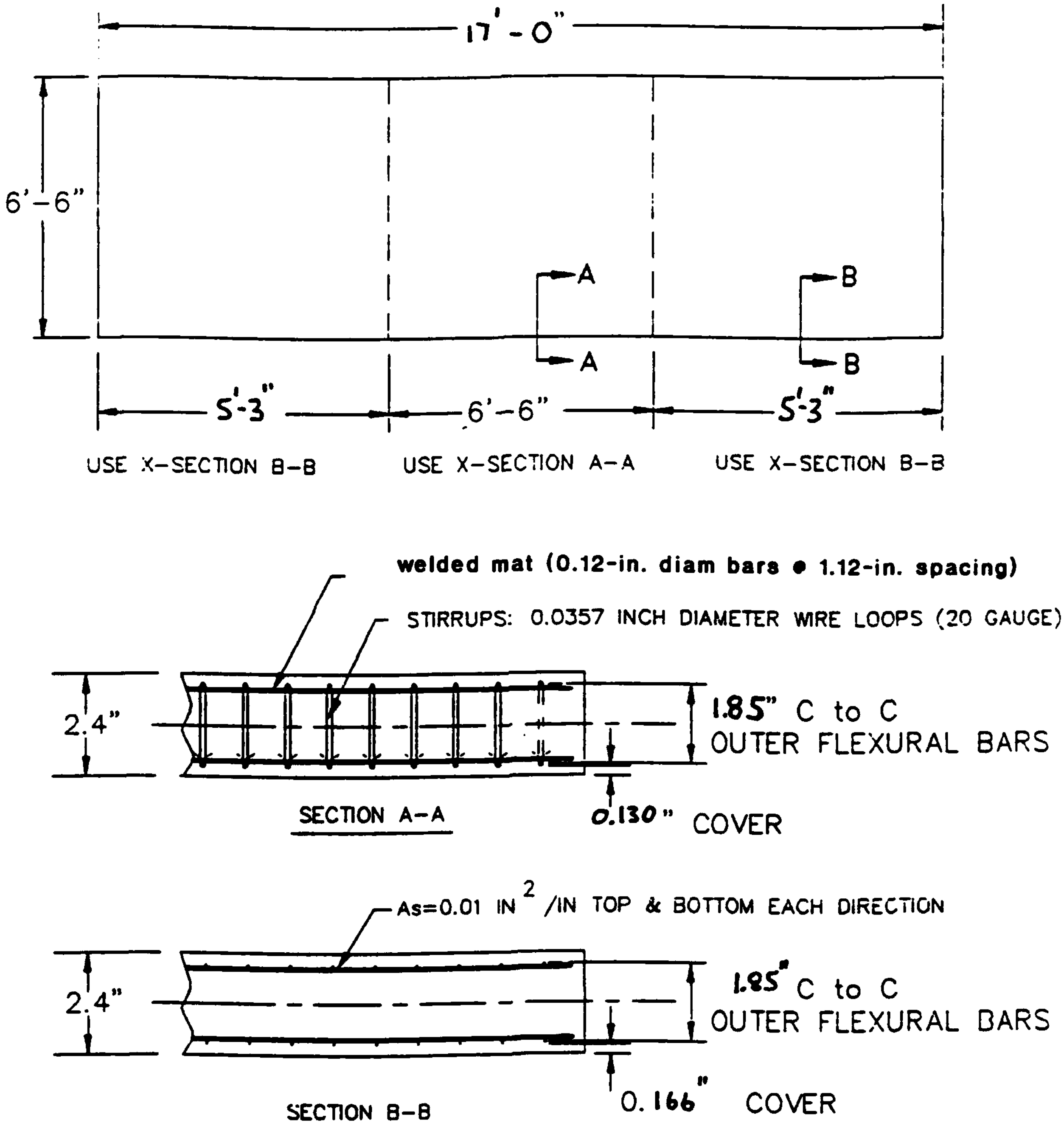


FIGURE 4. ROOF SLAB TEST SPECIMEN

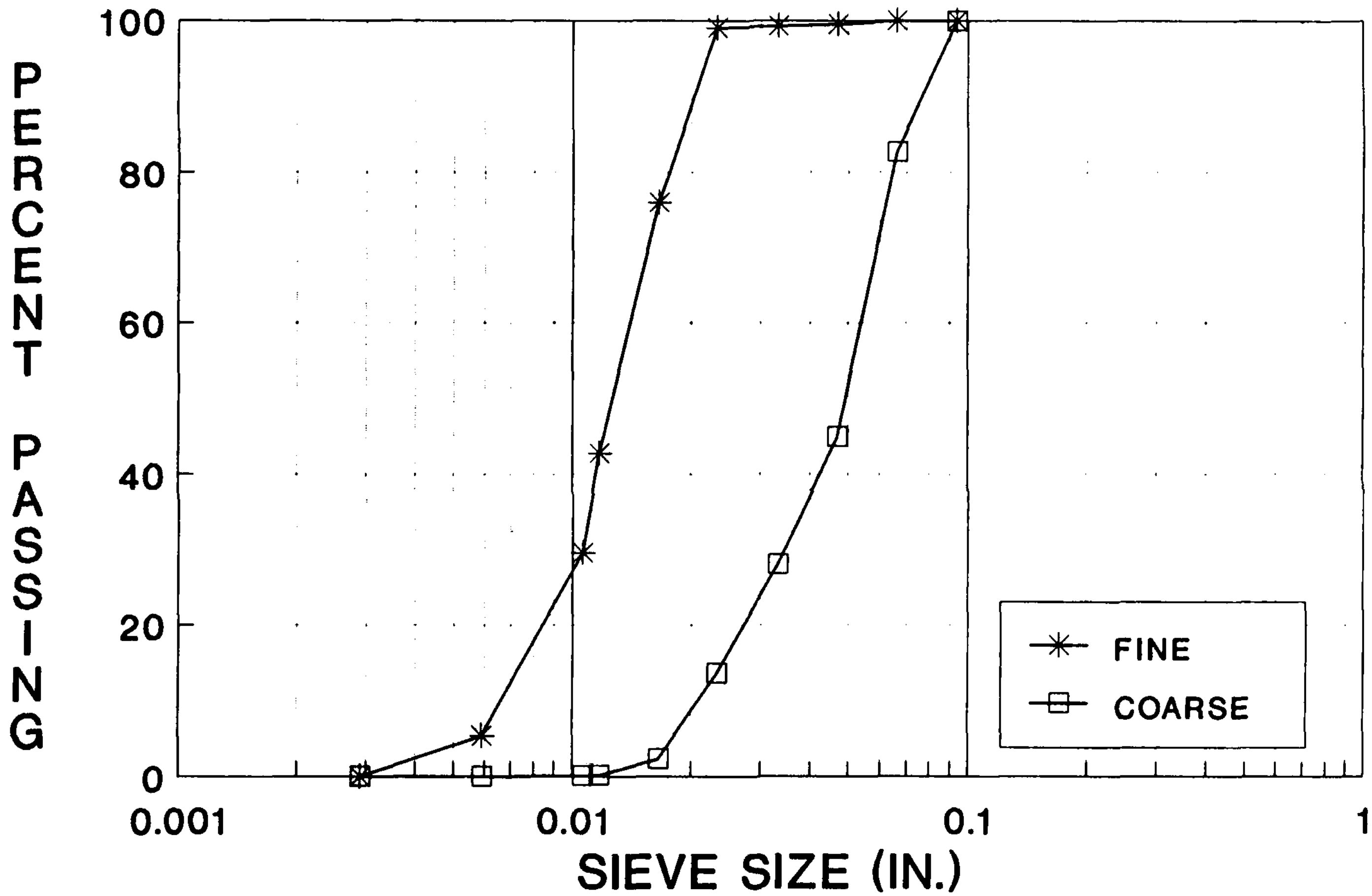


Figure 5. Aggregate distribution for 1/10-scale model concrete mix.

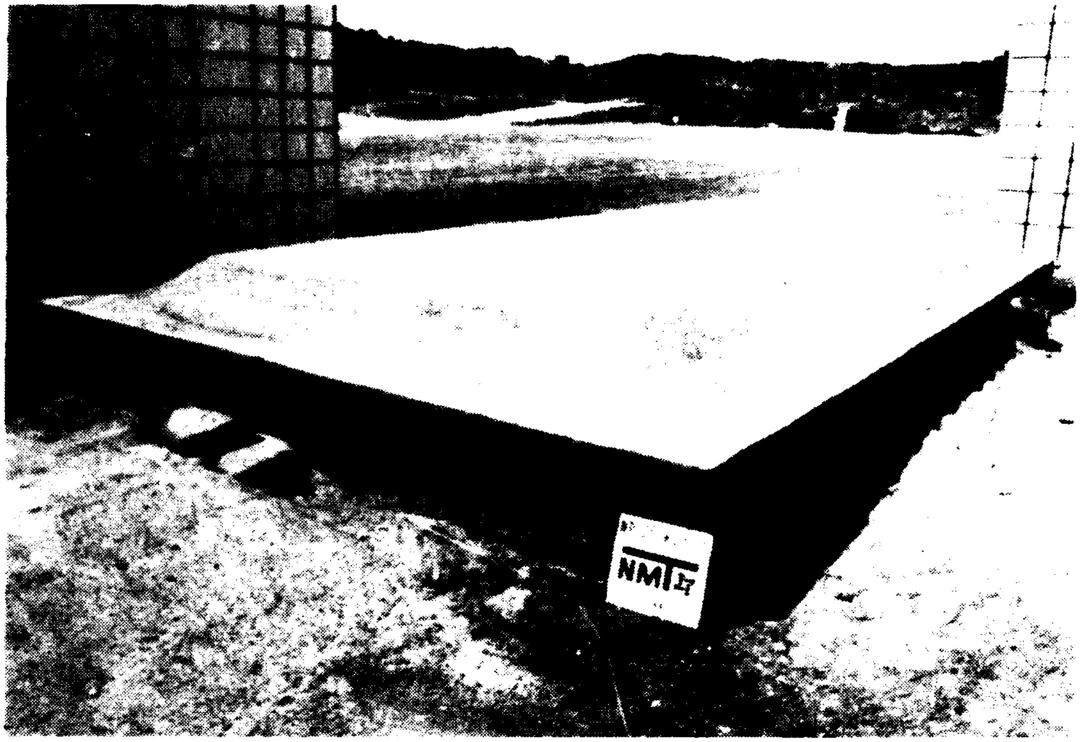


Figure 6. Roof specimen with soil cover.

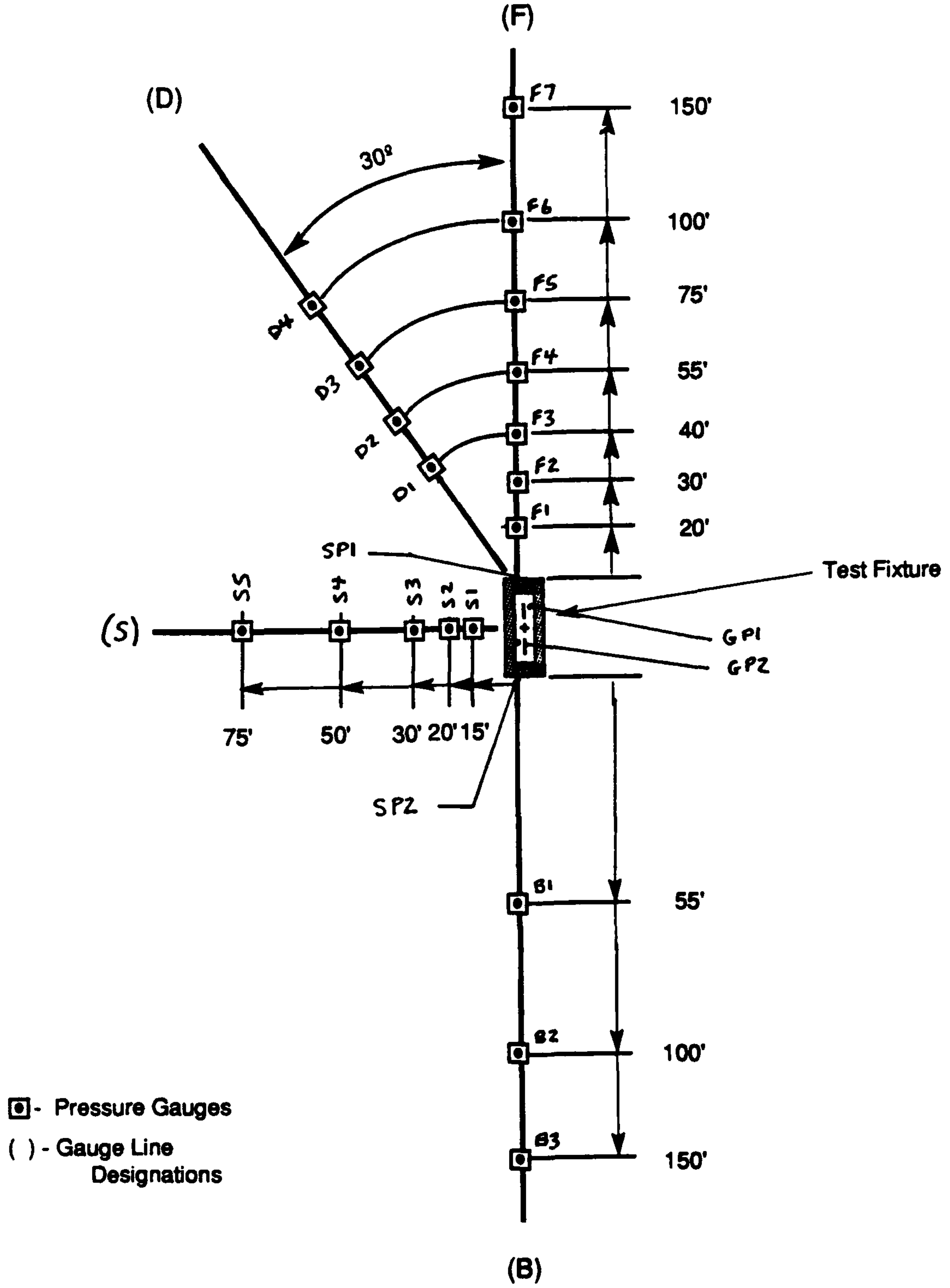
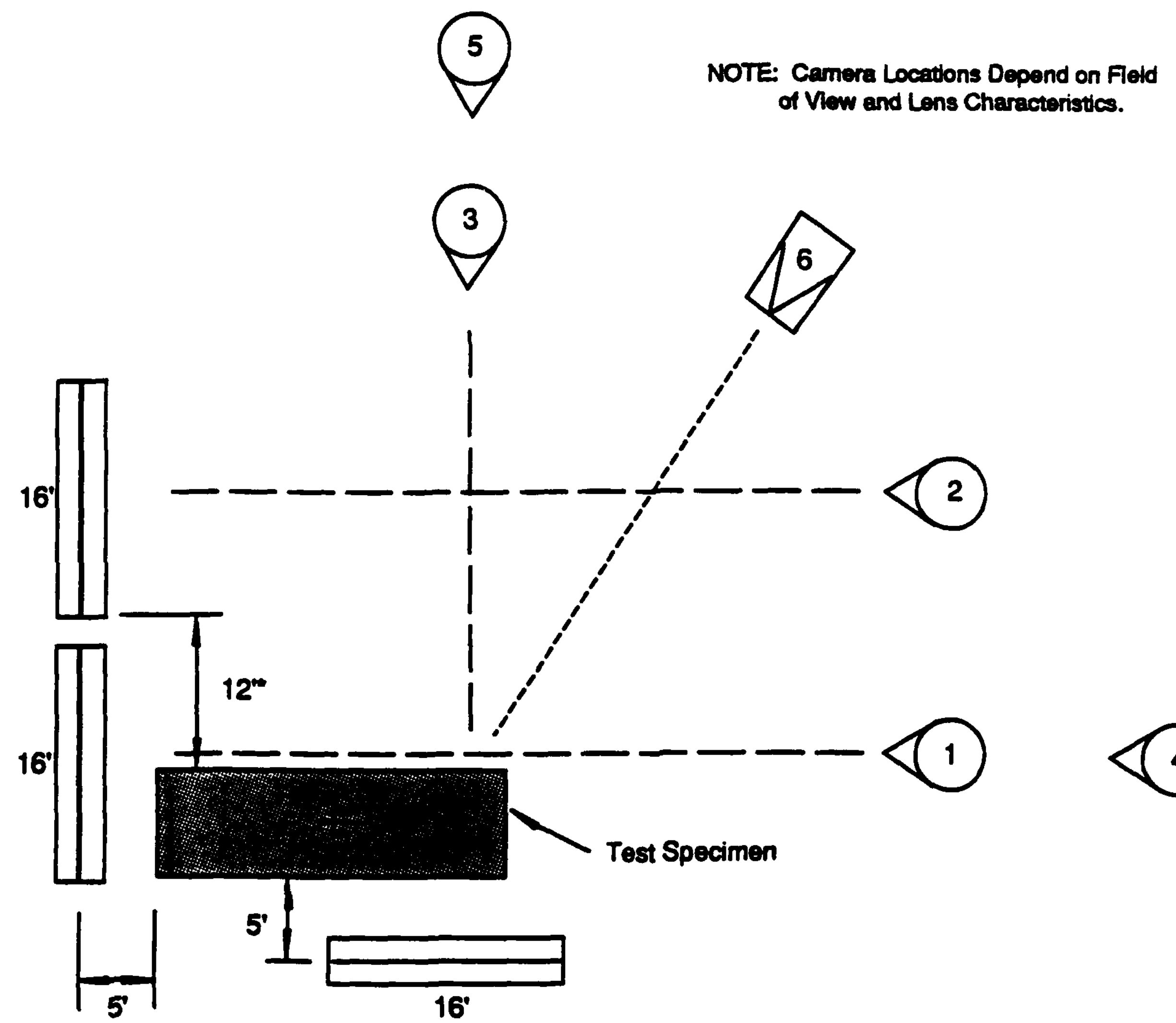


Figure 7. Pressure gauge locations.



Key:

- High Speed Movie Cameras
  1, 2, & 3: F.O.V. = 25' x 25';
  Frame Speed = 2000 fps
  4 & 5: F.O.V. = 200' x 200';
  Frame Speed = 2000 fps
- Real Time Video Camera
- Target: 16' x16' With 1' Grids on White Background; Bottom 1' Off Ground.
- Camera Line of Sight
- * Variable Dimension to Allow for Visibility Outside FireBall

Figure 8. Camera locations.

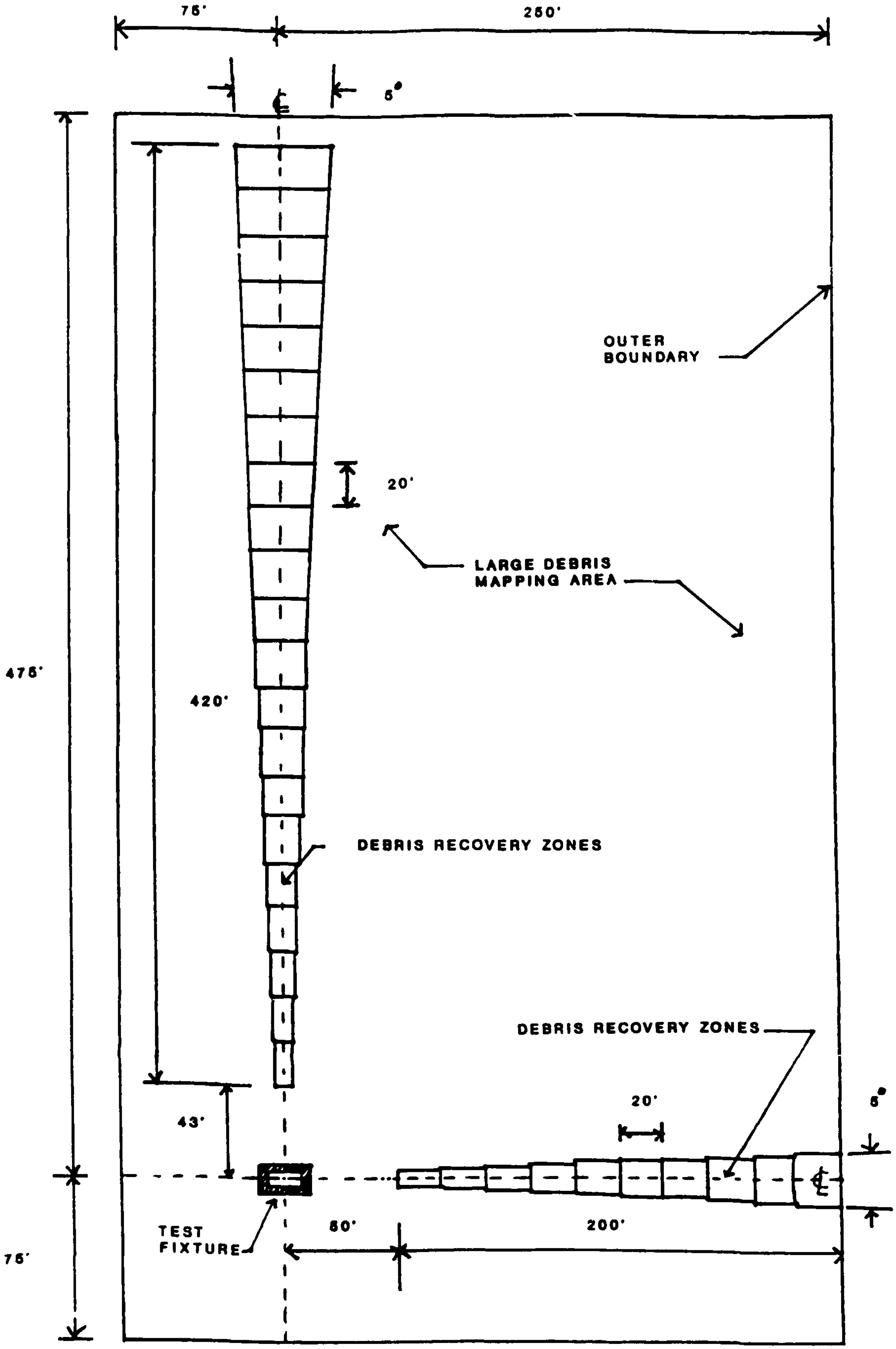
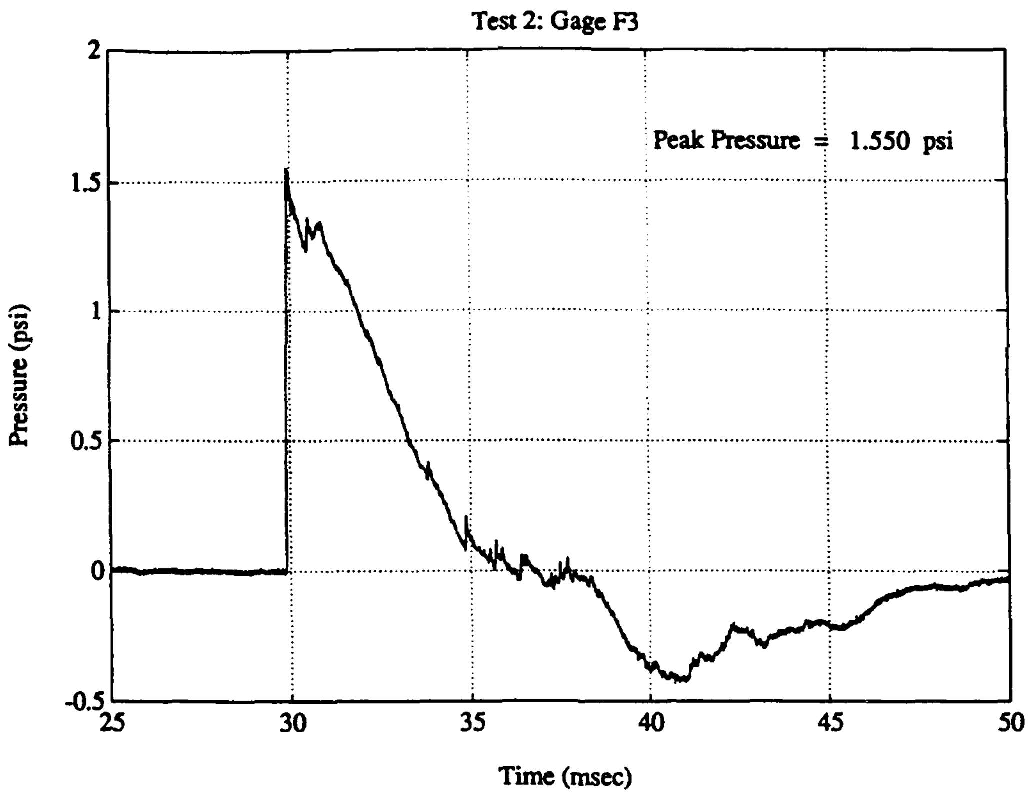


Figure 9. Debris recovery zones.



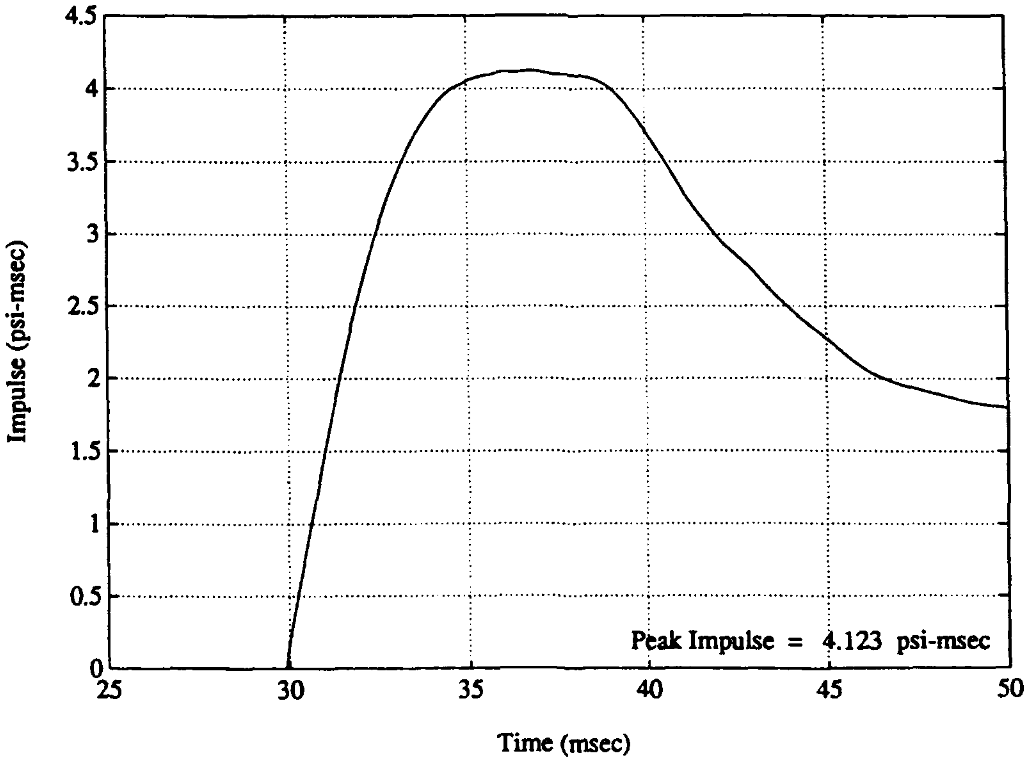


Figure 10. Pressure and impulse time histories for Guage F3, Test 2.

Figure 11. Post-test overall view of Test 1 roof.

Figure 12. Post-test close-up view of Test 1 roof.

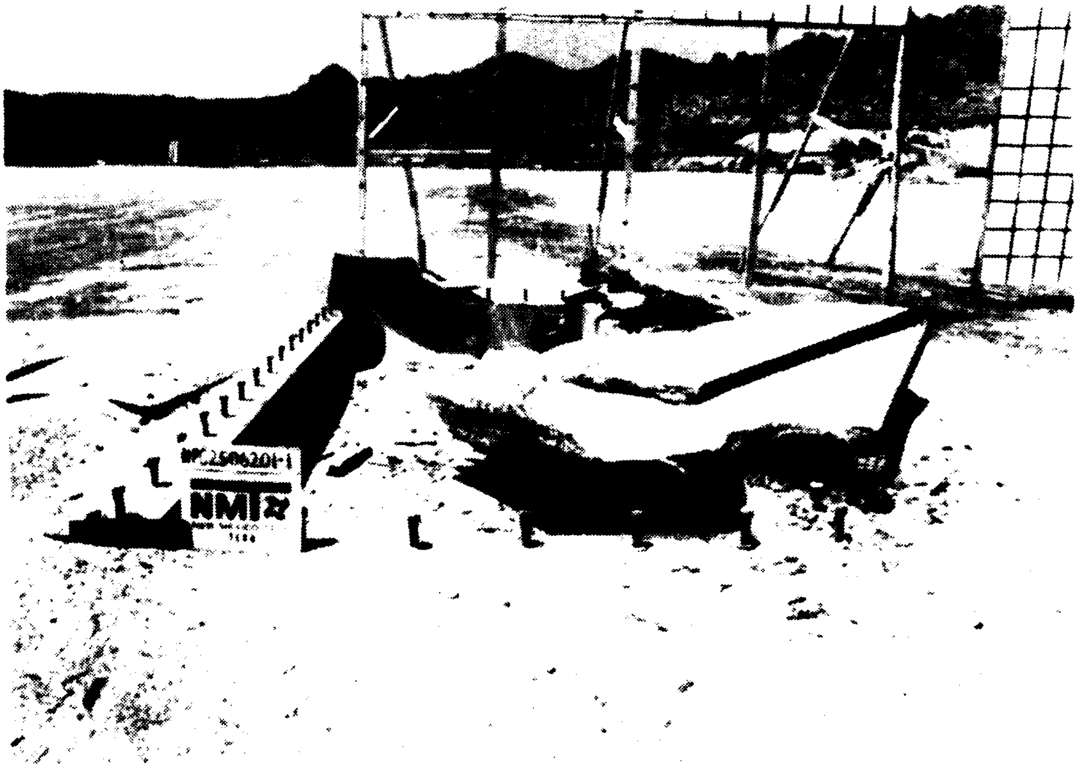


Figure 13. Post-test overall view of Test 2 roof.

Figure 14. Post-test close-up view of Test 2 roof.

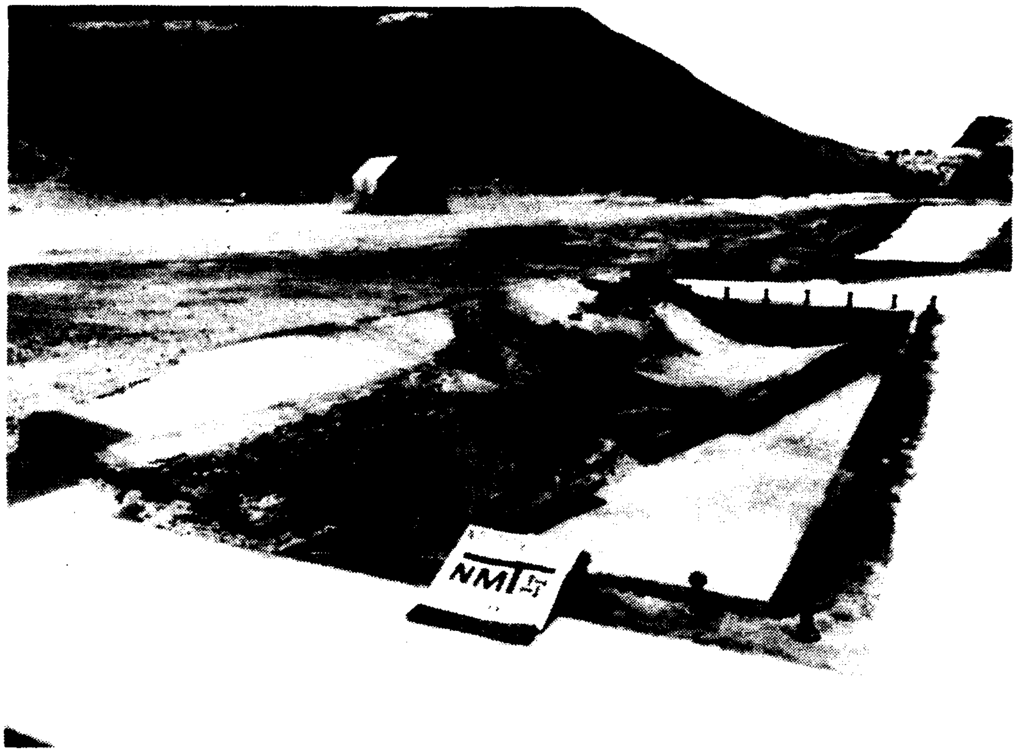


Figure 15. Post-test overall view of Test 3 roof.

Figure 16. Post-test close-up view of Test 3 roof.

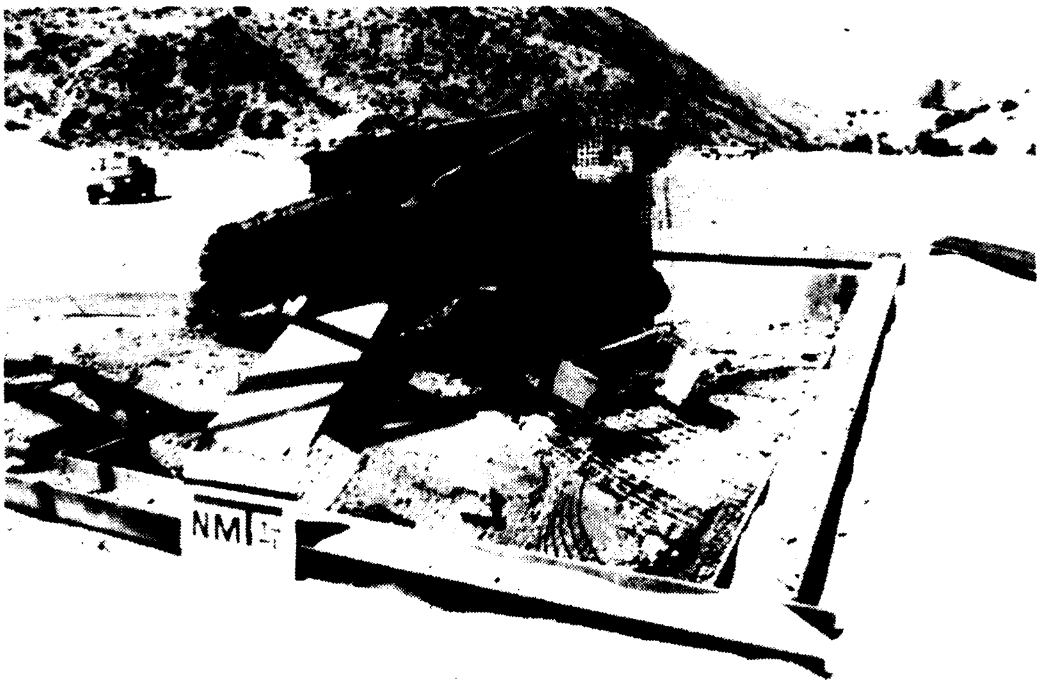


Figure 17. Post-test overall view of Test 4 roof.

Figure 18. Post-test close-up view of Test 4 roof.

Figure 19. Post-test close-up view of Test 5 roof.

Figure 20. Post-test overall view of Test 6 roof.

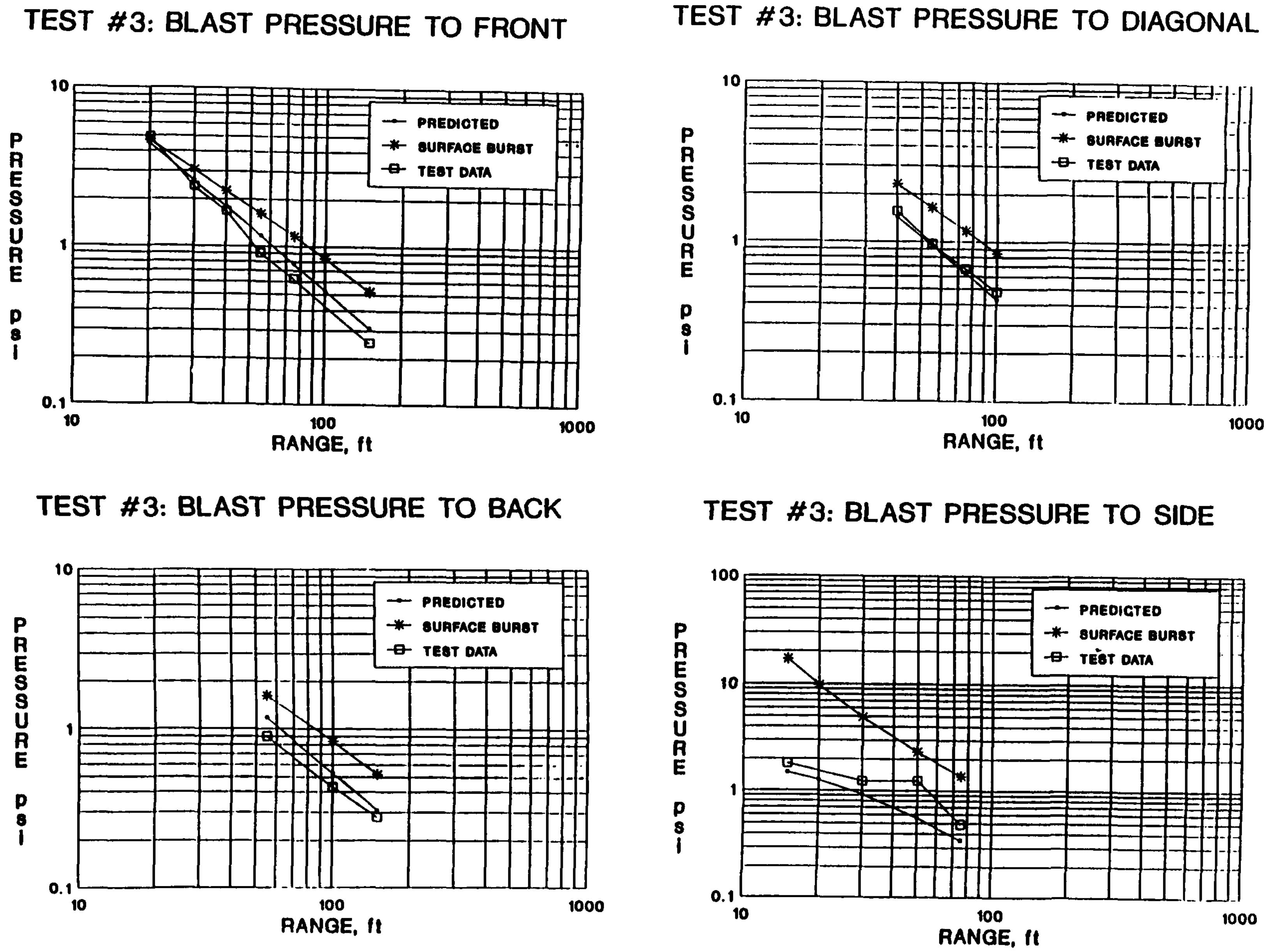


Figure 21. Peak pressure vs. range for Test 3.

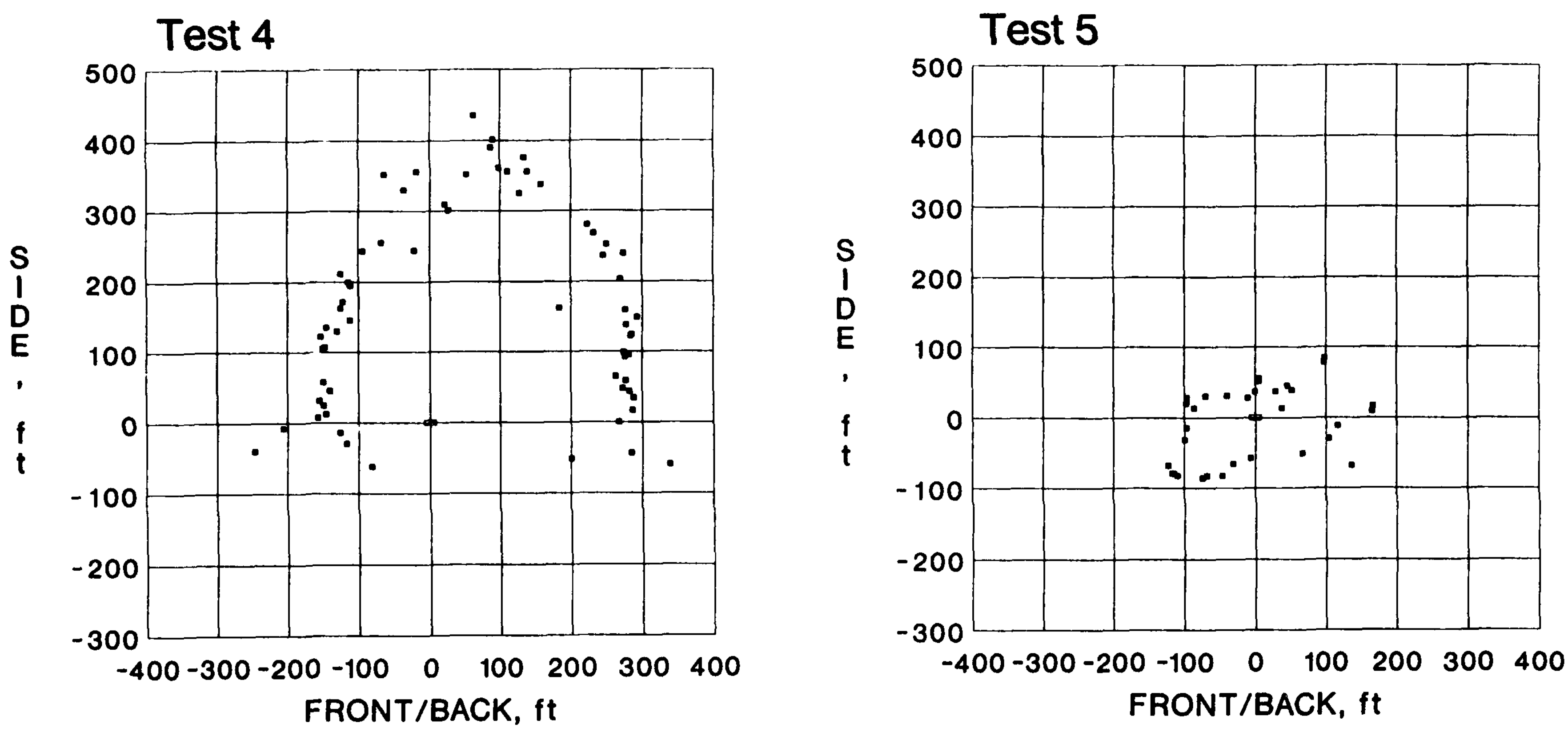


Figure 22. Location of debris collected outside recovery zones for Tests 4 & 5.

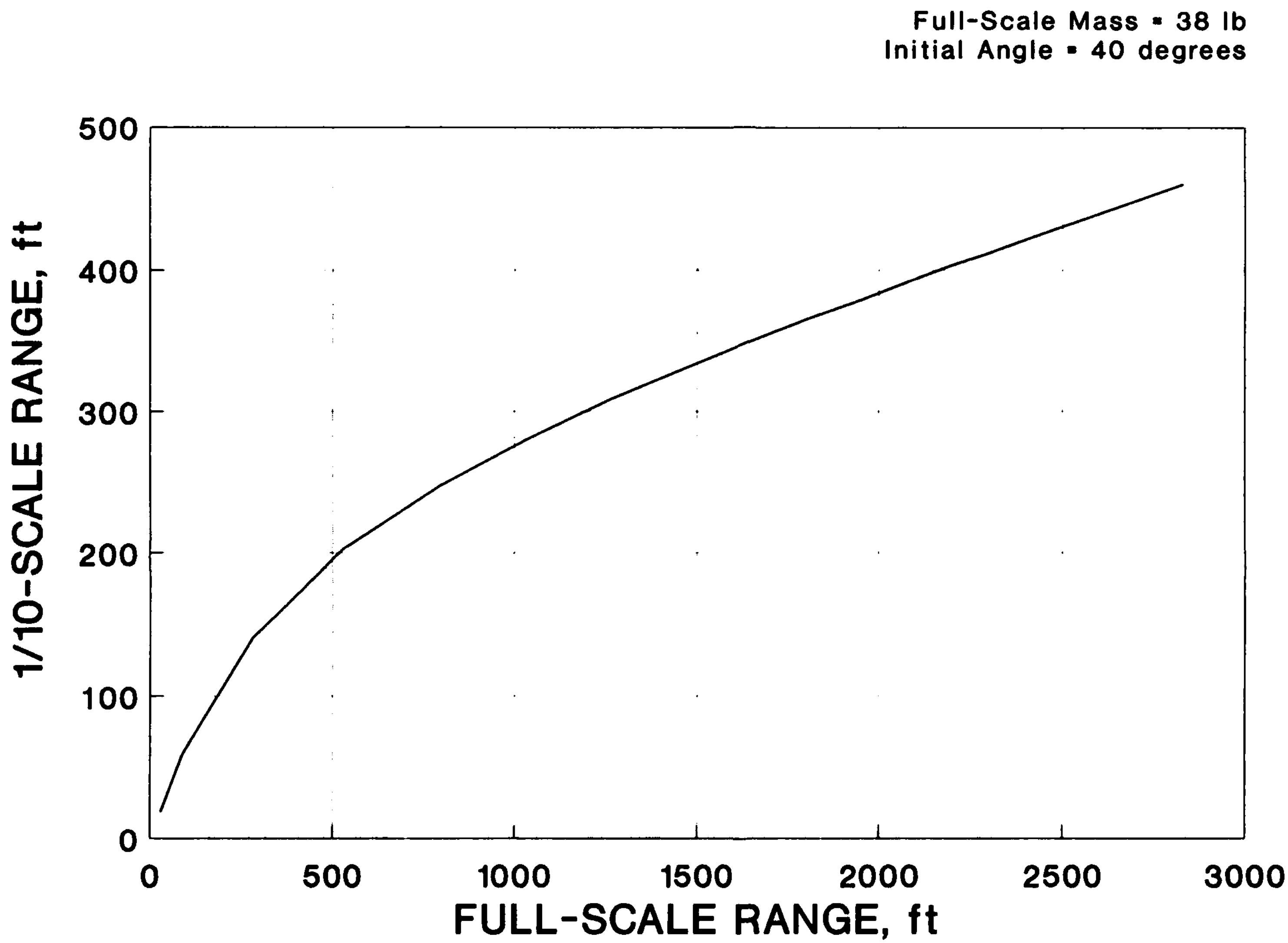


Figure 23. Full-scale vs. 1/10-scale debris distance relationship.

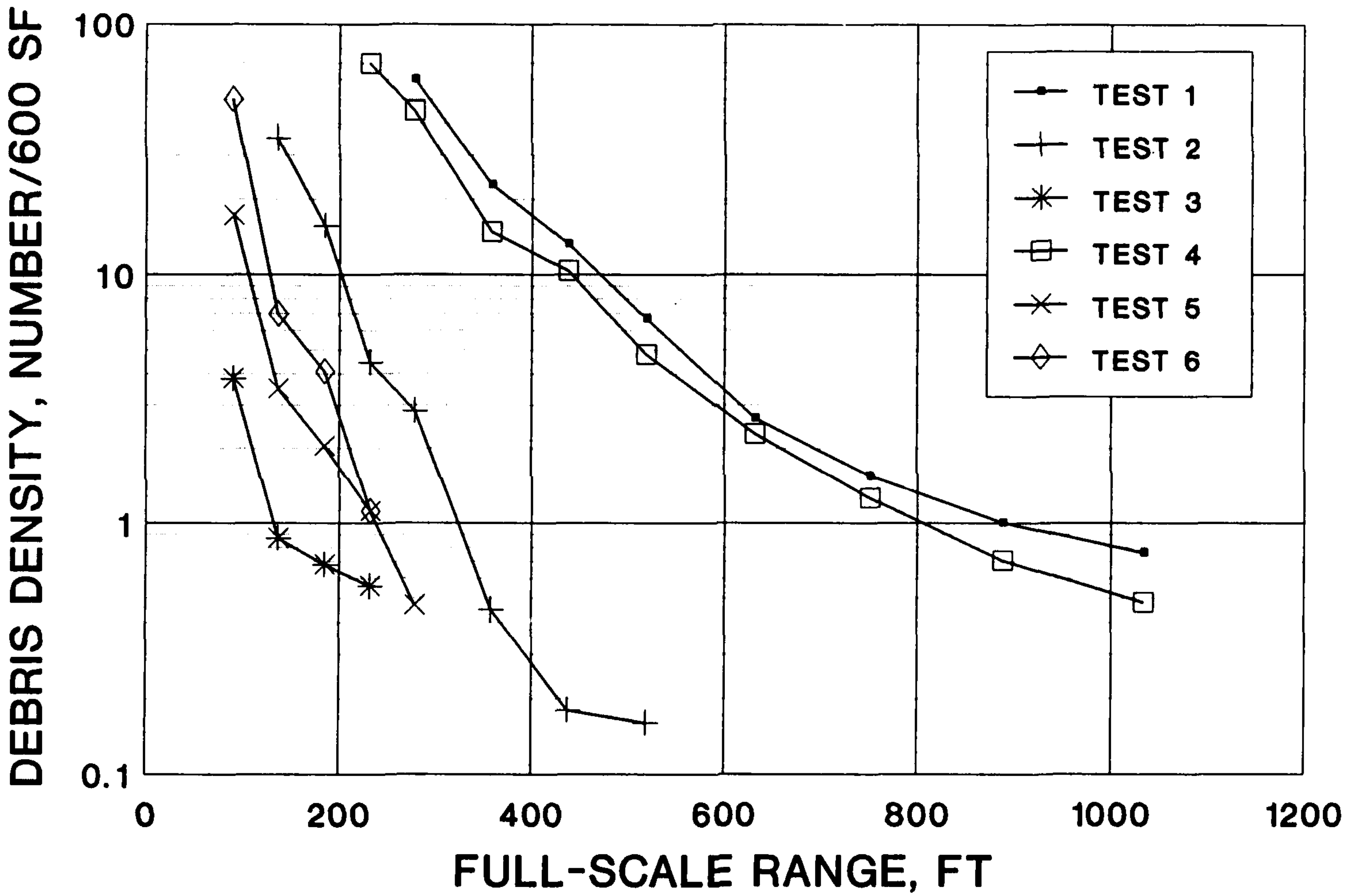


Figure 24. Debris areal number density distribution in side direction for Tests 1-6.

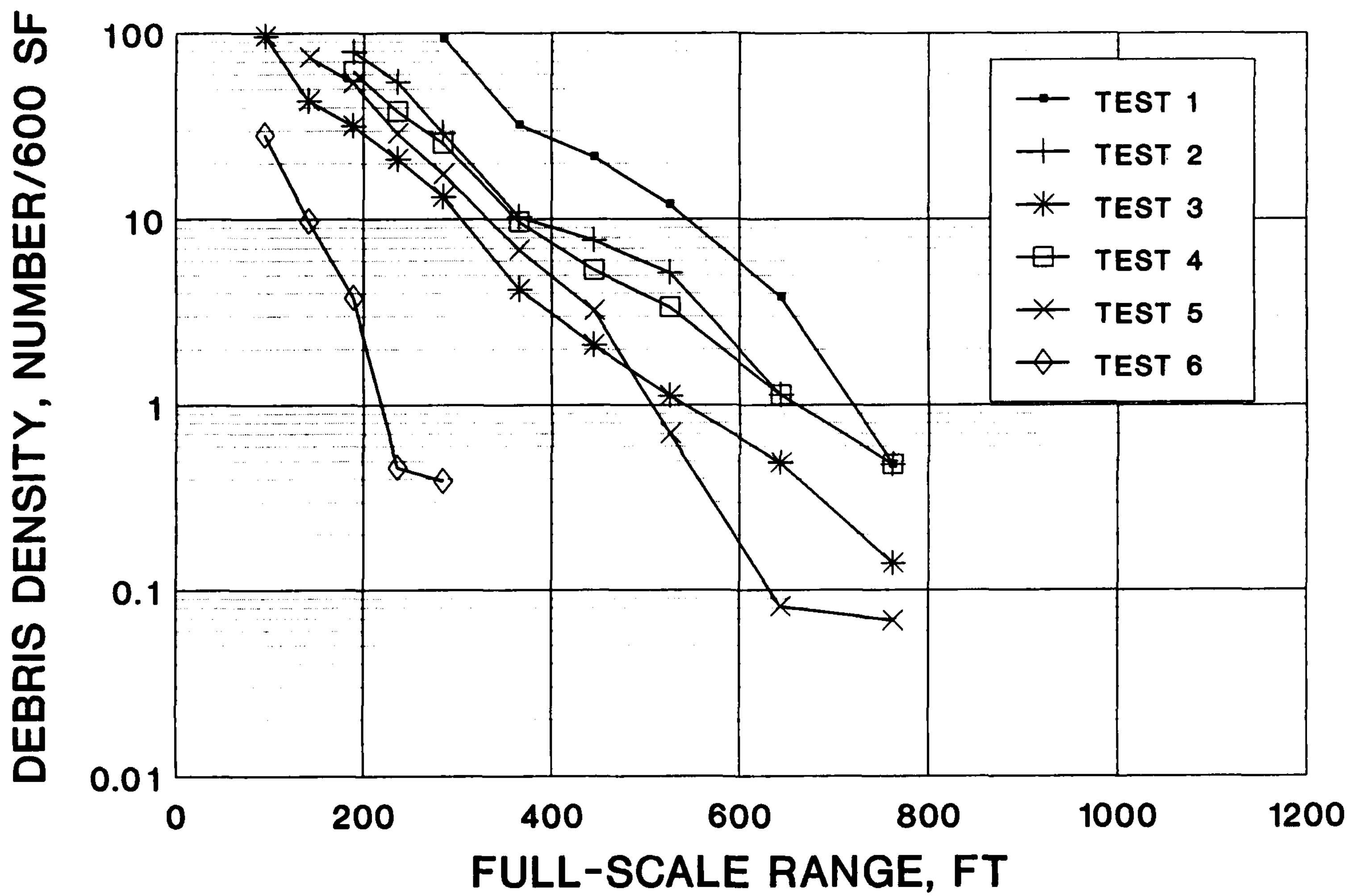


Figure 25. Debris areal number density distribution in front direction for Tests 1-6.

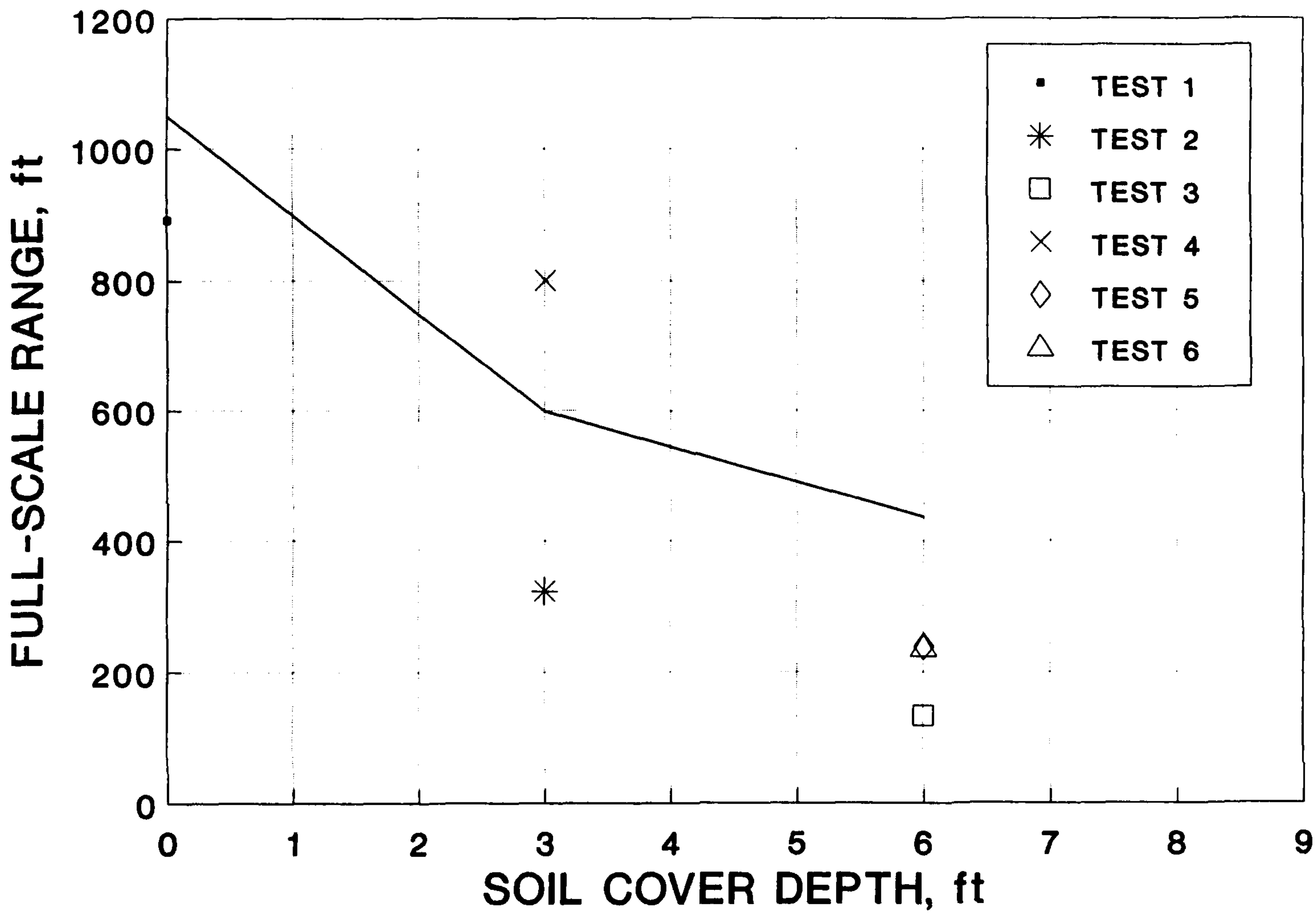


Figure 26. Measured vs. predicted full-scale safe debris range in side direction.

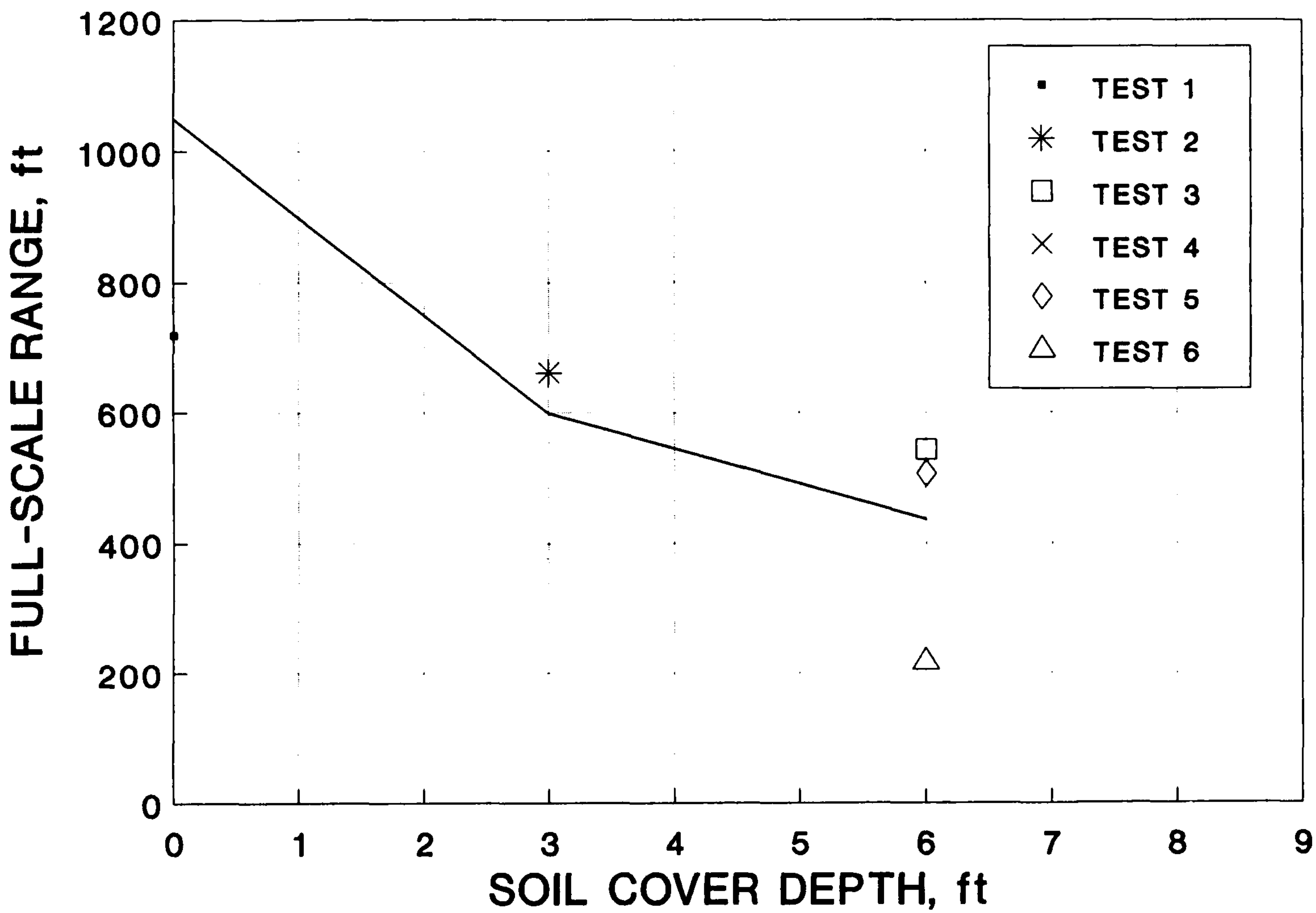


Figure 27. Measured vs. predicted full-scale safe debris range in front direction.

AUTODYN 2D PREDICTIONS FOR SMALL SCALE HP MAGAZINE CELL WALL TESTS

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BACKGROUND

Concept

The Naval Civil Engineering Laboratory is developing a new magazine concept that will reduce the land area encumbered by ESQD arcs and improve the efficiency of weapons handling operations. This new High Performance Magazine (HP Magazine) can reduce encumbered land by 80% and significantly reduce operational costs. The most important factor in the improved performance of the HP Magazine is the reduction of the Maximum Credible Event (MCE) to the Net Explosive Weight (NEW) of High Explosive (HE) in an individual storage cell. Internal cell walls are being developed to mitigate the effects of an explosion in any cell and prevent sympathetic detonation in adjacent cells. The performance of the HP Magazine is also enhanced by soil cover and tunnel type exits that reduce the safe distance for debris and overpressure. The MCE in a magazine storing conventional palletized weapons (e.g. bombs, projectiles, mines) would be reduced from about 200,000 lbs to about 10,000 lbs. The MCE for missile storage would be reduced from 100,000 lbs to 10,000 lbs. The preliminary HP Magazine concept and its key components are shown in Figure 1.

Benefits

Current magazine technology limits the net explosives load to about 350 lbs per acre of encumbered land. The HP magazine could increase this to 3000 lbs per acre allowing up to an eight fold reduction in encumbered land. The following table summarizes the savings in encumbered land with an HP Magazine.

ENCUMBERED LAND
STANDARD VS HP MAGAZINE

STORAGE	STANDARD MAGAZINE		HP MAGAZINE		REDUCED
	ESQD ARC	AREA	ESQD ARC	AREA	AREA
(lbs)	(ft)	(acres)	(ft)	(acres)	(%)
200,000 (Conv.)	2680	518	1000	72	86
100,000 (Missiles)	1625	190	750	40	79

Development Program

Major elements of the current development program are the characterization of the hazard, and the development of mitigation methods. The internal cell wall is a major component in the prevention of sympathetic detonation within the magazine.

In the past, testing has been required to obtain verification and acceptance of designs to prevent sympathetic detonation. Application of the results were also limited to the test configuration. It would be impossible to test all possible HP Magazine configurations and ordnance storage layouts. Therefore, development and verification of prediction models is critical to the success of the program. NCEL has been developing state of the art finite element and hydrocode models (primarily DYNA3D and AUTODYN) to predict the wall and acceptor response.

Scope of Paper

This paper presents the small scale wall development test program and the analytical techniques used to predict the wall and acceptor response. Limited test data is compared to predictions.

CELL WALL SMALL SCALE DEVELOPMENT TEST PROGRAM

Test Objectives

The objectives of these small scale tests are:

(a) to obtain data to verify and improve the analytical models which predict donor loads, wall response, acceptor loads, and acceptor response.

(b) to show the effects of specific wall design variables on the acceptor loads.

(c) to determine the wall response and acceptor loads in a $1/3^{rd}$ scale model wall test.

Scope of Test Program

Eight small scale tests are being conducted in two phases at the Naval Air Warfare Center (NAWC), China Lake. Test variables include wall mass, wall core material, wall cover material, and acceptor orientation. The configurations for Phases I & 2, Tests 1 to 8, are shown in Table 1. Figure 2 shows a typical test setup.

The tests are designed to determine the effects of design parameters on acceptor loads and response. The wall core materials (water, sand, and steel grit), wall cover materials (aluminum honeycombs and a low density

chemically bonded ceramic from CEMCOM Corp.), and acceptor orientation (parallel and perpendicular to the wall) are variables. The side by side parallel orientation of acceptors will also measure loads from acceptor impact on an adjacent acceptor.

Tests 1 through 6 are not true scale models of the prototype wall but were designed to show the relative effects of the different core and cover materials, to verify the prediction modeling, and to develop instrumentation capabilities under a less severe environment than would be obtained with a true scale model test. Tests 7 and 8 are $1/3^{rd}$ scale model tests of the critical HP Magazine cell sidewall for Mk82 bomb storage.

Test Setup

The Naval Air Warfare Center (Code 3269), China Lake, CA, is constructing the test setup and conducting the tests. Typical test setup dimensions are shown in Figure 2. Details of the planned test setups can be obtained from the test plan (NCEL TM 51-92-01: Small-Scale HP Magazine Cell Wall Development Test Plan by Kevin Hager and James Tancreto, June 1992). The final test report will detail the actual test setups and conditions.

Cell Walls. Table 1 shows the wall dimensions and materials. Plywood containers are being used to hold the wall core (water, sand, steel grit). Many walls use energy absorbing cover materials opposite the acceptor. The cover materials include crushable aluminum honeycombs with 800 and 1450 psi static crushing strengths, and a CEMCOM Corp. high void ratio, light weight, chemically bonded ceramic (SA/CBC GC2).

Explosive Donor. One and two Mk 82 bombs are used as donors. All donors are oriented parallel to the test walls with their center of gravity at 2 feet above the floor slab. A single Mk82 donor will be centered between the two test walls in parameter Tests 1 through 6. Tests 7 and 8 will use two side by side Mk 82 donors to achieve $1/3^{rd}$ scale model loads. The nominal explosive weight for a MK 82 is 200 lbs.

Inert Acceptors. Two instrumented inert M107-155m projectile acceptors are located opposite each test wall.

Data Acquisition

The acceptor response is being measured with self-contained accelerometers provided, installed, and operated by the U.S. Army Waterways Experiment Station (WES), Explosives Effects Division. WES is analyzing the accelerometer data and is providing acceleration, velocity, and displacement time histories. Passive structural response gages are being used to indirectly obtain the wall loadings on square and cylindrical shapes. High speed camera data will be used to obtain acceptor trajectory (initial angle and velocity of acceptors) information.

DEVELOPMENT TEST LOADS AND RESPONSE PREDICTIONS

Analysis of the small-scale cell wall test setup included two-dimensional load predictions on the cell wall, one-dimensional wall and acceptor response, and two-dimensional wall and acceptor response. The "hydrocode" AUTODYN 2D (Century Dynamics Corp.) was used for these analyses. One-dimensional models were used to provide a timely prediction of parameter effects for use in early test planning. The two dimensional model computations, which take considerably more computer time, are being conducted to obtain better response predictions. Model variables include wall mass, wall materials, energy absorbing wall cover materials, acceptor orientation, and donor charge weight.

The calculations were limited by the lack of proven equations of state (EOS) for the wall materials. Tests are planned to obtain equations of state for the steel grit, sand, and CBC materials used in the tests. Because of the current uncertainties in the equations of state, we are limiting the discussion of these preliminary analyses to wall models with sand cores. These models used an existing sand EOS and estimated EOS's for cover materials. Typical results are shown and discussed. Predictions for all models that have been run are shown in Table 2. Predictions will improve as better equations of state are developed.

Wall Loads

The pressure time-history on the donor side of the test wall was calculated using a two-dimensional Euler grid. The two-dimensional calculations provided wall loads as a function of height. Prototype full scale wall loads were determined for the dense (high load) storage of MK 82 bombs. Scale model test configurations were then analyzed and compared to the desired full scale loading. Small "scaled" distances between the MK 82 donor and the cell wall are necessary to obtain the desired scale model loads and wall velocities.

A typical two-dimensional model is shown in Figure 3. Symmetry is used to model a test with two Mk 82 donors. One Mk82 donor is modeled as a cylinder of TNT parallel to the wall. A reflecting boundary on the vertical line of symmetry gives the solution to a test setup that includes a mirror image of the model shown in Figure 3 (i.e two Mk 82 bombs and two walls). The pressure time-histories on the donor side of the wall are shown at a few selected wall heights in Figure 4. The impulses at the same points are shown in Figure 5.

Wall Response

Figures 6 & 7 show the response of the sand wall in Figure 3. Figure 6 shows the wall as it impacts the acceptor. Horizontal wall velocities varied from 390 m/s (bottom) to 116 m/s (top). Figure 7 shows the sand flow around the acceptor 1.1 ms after first impact.

One-Dimensional Acceptor Response

The one-dimensional analysis provided a timely and generally conservative prediction of acceptor loads, accelerations and velocities. Results were used to show relative effects of variables on acceptor response. The rigid body accelerations were also used to size and calibrate the accelerometers placed within the 155mm projectile acceptors.

The test wall, energy absorbing cover materials, and acceptors were modeled with LaGrange finite-difference grids. Impact-slide elements on the grid boundaries calculated contact forces between the grids. The acceptors were modeled as solid steel cylinders with the same weight and outside diameter as the inert 155mm projectiles used in the tests. Predicted response is shown in Table 2.

Typical Model Results. Typical analysis results are shown in Figures 8 to 12. Figure 8 shows the model for a 36" sand wall with and without a 10" thick 800 psi honeycomb cover. Figures 9 and 10 compare the pressure loads for the two models. The energy absorbing honeycomb cover significantly reduces the acceptor pressure load (Figure 8) and increases the load duration.

Figures 11 and 12 show the velocity time-histories of the acceptors and walls for the two models. Acceptor accelerations can be obtained from the slopes of the velocity-time curves. The sand wall without honeycomb cover produces an acceptor acceleration of 1.8kg (see Figure 11). The acceptor acceleration is reduced to 0.28 kg with the addition of the aluminum honeycomb.

The energy absorbing cover significantly reduces peak pressure and acceleration loads while the final velocity of the acceptor is not significantly affected.

Two-Dimensional Acceptor Response

Two-dimensional analysis used the same material models and boundary conditions, and LaGrange grids as the one-dimensional model. The two dimensional model allows wall material flow around the acceptor and accounts for the additional loads from the presented area of the 800 psi honeycomb (which is greater than the acceptor area). Predicted response is shown in Table 2.

Typical Model Results. Typical analysis results are shown in Figures 13 to 20. Figures 13 to 16 show material locations and acceptor velocities for a single Mk 82 donor and a 36" sand wall, with and without an 800 psi honeycomb cover. The material locations are shown at times when the acceptor velocities are approaching their maximum. Figures 13 and 15 show the sand flow around the acceptor. Although the honeycomb reduces the acceleration on the acceptor it presents a larger area to the sand flow and produces higher loads and velocity for the acceptor (compare Figures 14 and 16). Likewise, the 2-D model with honeycomb predicts higher acceptor velocities than the 1-D model.

Two-dimensional model results of the 1/3 rd scale 12" sand wall, loaded by 2 Mk 82 donors, are shown in Figures 17 and 18. The velocity of the 12" sand wall is about 200 m/s on impact with the acceptor. Figure 17 shows the wall at about 2.8 ms after impact with the acceptor. The acceptor velocity is shown in Figure 18. The peak velocity of the acceptor is about 27 m/s.

TEST RESULTS VS. PREDICTIONS

Limited preliminary test results are now available. Table 3 compares preliminary test results to predictions for 36" sand walls, with and without cover materials, and with loads from one donor (about 200 lbs of high explosive). The wall velocities generated in the sand wall tests were about 50 m/s. Table 4 compares preliminary test results and predictions for steel grit walls, with and without cover materials, and with loads from two donors (about 400 lbs of high explosive). The wall velocities generated in the tests of 8" steel grit walls were about 100 m/s.

Parallel Acceptors

Sand Wall without Cover. Data for Acceptor 1, parallel and 6" from a 36" sand wall, is shown in the first two lines of Table 3. Acceptor 1 is located between the sand wall and Acceptor 2 (see Figure 2). The first line of data shows the effect of the sand wall impact on Acceptor 1. Measured accelerations and velocities were bounded by the 1D and 2D AUTODYN predictions.

The second line of data shows the response of Acceptor 1 from impact with Acceptor 2. Predicted peak accelerations were high because of the simple elastic model used for the acceptors (plastic deformation, which would have reduced the peak accelerations, was not accounted for in the analytical model). The maximum velocity was close to that predicted by the 2D model.

Steel Grit Wall with Cover. Table 4 (lines 1 to 3) shows the measured and calculated acceptor response in a test setup with two donors and an 8" steel grit wall with 12" CBC cover (between the steel grit and the acceptor). Acceptor velocities were slightly less than the conservative 1D model predictions. The measured acceleration on acceptor 1, from impact of the CBC/steel grit wall, was about 50% higher than predicted. As expected, measured accelerations from collision of Acceptor 1 with Acceptor 2 were significantly less than predicted because of the use of a solid elastic material in the acceptor model.

Perpendicular Acceptors

Sand Wall without Cover. The response of acceptors perpendicular to a sand wall, without energy absorbing cover materials, is shown in line 3 of Table 3. The peak acceleration was about one half the predicted value. The peak velocity was about $2/3^{rds}$ the predicted velocity.

Sand Wall with Cover. Measured peak acceptor accelerations, when energy absorbing covers were used on the wall (lines 4 and 5 in Table 3), were close to predictions. The aluminum honeycomb reduced the peak accelerations on the acceptor (vs. a sand wall without a cover). With 1 donor (wall velocities around 50 m/s) the CBC material (with a static crushing strength of 2,000 psi) actually increased the peak acceleration of the acceptor. Measured velocities were less than the 2D predictions but higher than the 1D predictions. The 2D predictions are higher than the 1D predictions because they account for the increased loading area of the cover material (compare Figures 8 and 15).

Steel Grit Wall without Cover. Table 4 (line 4) shows the response of an acceptor perpendicular to an 8" steel grit wall without a cover material. The measured and predicted accelerations compared well, considering that an assumed steel grit EOS was used in the analytical model. The measured velocity, however, was 50% higher than predicted. This shows the need for development of a better steel grit EOS for use in future calculations.

Steel Grit Wall with Cover. Table 4 (lines 5 and 6) shows the response of acceptors behind an 8" steel grit wall with energy absorbing cover materials. The use of cover materials significantly reduced the measured acceptor accelerations (by a factor of 10) and velocities (by a factor of 2.5). At the wall velocities in these tests, the CBC was more effective than the aluminum honeycomb.

PRELIMINARY FINDINGS

These findings are based on first generation AUTODYN models. Better models are being developed to improve predictions. Test results are from first look data obtained in tests conducted this month. Final conclusions may differ from these preliminary findings.

- Because 1D analytical models restrict vertical flow, they generally predicted higher velocities and accelerations than 2D models.

- Variations in 1D and 2D model predictions for acceleration, in walls without energy absorbing covers, were greater with increased wall velocity.

- Wall energy absorbing cover materials with higher crushing strength produce higher acceptor accelerations. This effect diminished with increasing wall impact velocity.

- Good correlation was generally obtained between predicted and measured acceptor velocities. When large differences occurred, they could be attributed to an assumed EOS. Measured and calculated acceptor accelerations, in many cases, show large differences. This is attributable to inaccuracies in modeling and to the interpretation of calculations and measurements (e.g. peak acceleration vs. average change in velocity over critical time step).

- Test results from a 200 lb HE donor load on 36" sand walls (wall velocity = 50 m/s) show lower impact accelerations on the acceptor from the sand wall than predicted. The mitigating effect of energy absorbing aluminum honeycomb was less than expected (relative to sand wall without honeycomb). The stronger and more brittle CBC cover material did not mitigate wall impact loads at these low sand wall velocities (less than 50 m/s).

- Test results from a 400 lb HE donor load on 8" steel grit walls show that the aluminum honeycomb and the CBC are very effective at reducing acceptor accelerations at higher wall velocities (100 m/s). Preliminary results also show a reduction in acceptor velocities (vs. steel grit wall without cover materials).

- More accurate analytical modeling (planned for FY93) is needed to obtain better correlation with measurements.

Table 1. HPM SMALL SCALE WALL DEVELOPMENT TEST SCHEDULE

	#	DONOR	WALL ID	WALL T(in)	WALL CORE	WALL SKIN(a)	ACCEPTORS #	ACCEPTORS ORIENT(b)
PHSE I	1	1Mk82	I	36	WATER	---	1,2	//
			II	36	SAND	---	1,2	//
	2	1Mk82	I	36	SAND	800HC	1	//
			II	36	SAND	---	1,2	//
	3	1Mk82	I	36	SAND	800HC	1	+
			I	36	SAND	---	2	+
			II	36	SAND	---	1,2	//
	4	1Mk82	I	36	SAND	1450HC	1	+
			I	36	SAND	---	2	+
			II	36	SAND	---	1,2	+
PASE II	5	1Mk82	I	36	WATER	800HC	1	+
			I	36	WATER	---	2	+
			II	36	SAND	800HC	1	+
			II	36	SAND	CBC	2	+
	6	1Mk82	I	12	STEEL(c)	---	1,2	+
			II	36	SAND	1450HC	1	+
			II	36	SAND	---	2	+
	7	2Mk82	I	8	STEEL(c)	CBC	1	+
			I	8	STEEL(c)	---	2	+
			II	8	STEEL(c)	CBC	1,2	//
	8	2Mk82	I	8	STEEL(c)	CBC	1	+
			I	8	STEEL(c)	---	2	+
			II	12	SAND	CBC	1	+
			II	12	SAND	---	2	+

(a) 800HC - 10" of Aluminum Honeycomb with 800 psi crush strength
1450HC - 10" of Aluminum Honeycomb with 1450 psi crush strength
CBC - 12" CEMCOM Corp. Chemically Bonded Ceramic (SA/CBC GC2)

(b) + - 155 mm Projectile perpendicular to wall
// - 155 mm Projectile parallel to wall

(c) Steel grit: SAE size - S170

Table 2. Small Scale HPM Wall Development Test Acceptor Response Predictions

TEST	DONOR	<---WALL--->		<---COVER--->		<---ACCEPTOR---				--->	
								<ACCELERATION(kg)>		<--VELOCITY(ms)-->	
#	(lbs)	T (in)	Core	T (in)	Cover	#	ORIENT (a)	1D Model	2D Model	1D Model	2D Model
1	200	36	Water	--	----	1	//	4.1		51	
						1(b)		-88		15	
		36	Water	--	----	2	//	90		46	
1,2,3	200	36	Sand	--	----	1	//	4.1	0.25	32	17.8
						1(b)		-51	-16	18.8	10.2
3	200	36	Sand	--	----	1	+	1.81	1.5	17.1	16
				10	800 H/C	2	+	0.28	0.5	15.1	24.3
4	200	36	Sand	10	1450 H/C	1	+	0.43		15	
5	200	36	Water	10	800 H/C	1	+				
		36	Water	--	----	2	+				
		36	Sand	10	800 H/C	1	+	0.28	0.5	15.1	24.3
		36	Sand	12	CEMCOM	2	+	1		16.2	
6	200	12	Steel	--	----	1	+	7.1		18	
		12	Steel	--	----	2	+	7.1		18	
		36	Sand	10	1450 H/C	1	+	0.43		15	
		36	Sand	--	----	2	+	1.81	0.3	17.1	16
7	400	8	Steel	12	CBC	1	+	1.31		27	
		8	Steel	--	----	2	+	27		37	
		8	Steel	12	CBC	1	//	3.75		54	
						1(b)		-86		32	
		8	Steel	12	CBC	2	//	89		46	
8	400	8	Steel	12	CBC	1	+	1.31		27	
		8	Steel	--	----	2	+	27		37	
		12	Sand	12	CBC	1	+	1.74	1.2	30	33
		12	Sand	--	----	2	+	22	7.7	39.3	28

(a) + = Acceptor located perpendicular to wall
// = Acceptor oriented parallel to wall
(b) at impact with acceptor 2

Table 3a. Acceptor Accelerations
Measured and Predicted
36" Sand Wall
1 Mk82 Donor

ACCEPTOR ORIENT. (a)	COVER MAT'L (b)	COVER T (in)	ACCELERATION (kg) CALCULATED 1D Model	ACCELERATION (kg) CALCULATED 2D Model	ACCELERATION (kg) <TEST>
//(c)	None		4.1	0.25	2.5
//(d)	None		-51	-16	-6.5
+	None		1.81	1.5	1.0
+	800 HC	10	0.28	0.5	0.53
+	CBC	12	1		1.3

Table 3b. Acceptor Velocities
Measured and Predicted
36" Sand Wall
1 Mk82 Donor

ACCEPTOR ORIENT. (a)	COVER MAT'L (b)	COVER T (in)	PEAK VELOCITIES (m/s) CALCULATED 1D Model	PEAK VELOCITIES (m/s) CALCULATED 2D Model	PEAK VELOCITIES (m/s) <TEST>
//(c)	None		32	17.8	20
//(d)	None		18.8	10.2	10
+	None		17.1	16	10.6
+	800 HC	10	15.1	24.3	18.2
+	CBC	12	16.2		18

(a) // : Acceptor parallel to wall
+ : Acceptor perpendicular to wall
(b) 800 HC : 800 psi Aluminum Honeycomb
CBC : CEMCOM Inc, Type SA/CBC GC2
(c) Acceptor 1 response from wall impact
(d) Acceptor 1 response from impact with adjacent acceptor 2

Table 4. Acceptor Response
Measured and Predicted
8" Steel Grit Wall
2 Mk82 Donors

ACCEPTOR ORIENT. (a)	COVER MAT'L (b)	<-ACCELERATION(kg)-> CALCULATED 1D MODEL	TEST	<--VELOCITY(m/s)--> CALCULATED 1D Model	TEST
//(c)	CBC	3.8	6	54	38
//(d)	CBC	-86	-21	32	23
//(e)	CBC	89	12	46	38
+	None	27	33	37	56
+	800 HC	9	3.3	31	23.5
+	CBC	1.31	1.7	27	21.5

(a) // : Acceptor parallel to wall
+ : Acceptor perpendicular to wall
(b) 800 HC : 800 psi Aluminum Honeycomb
CBC : CEMCOM SA/CBC GC2 Chemically Bonded Ceramic
(c) Acceptor 1 response from wall impact
(d) Acceptor 1 response from impact with acceptor 2
(e) Acceptor 2 response from impact with acceptor 1

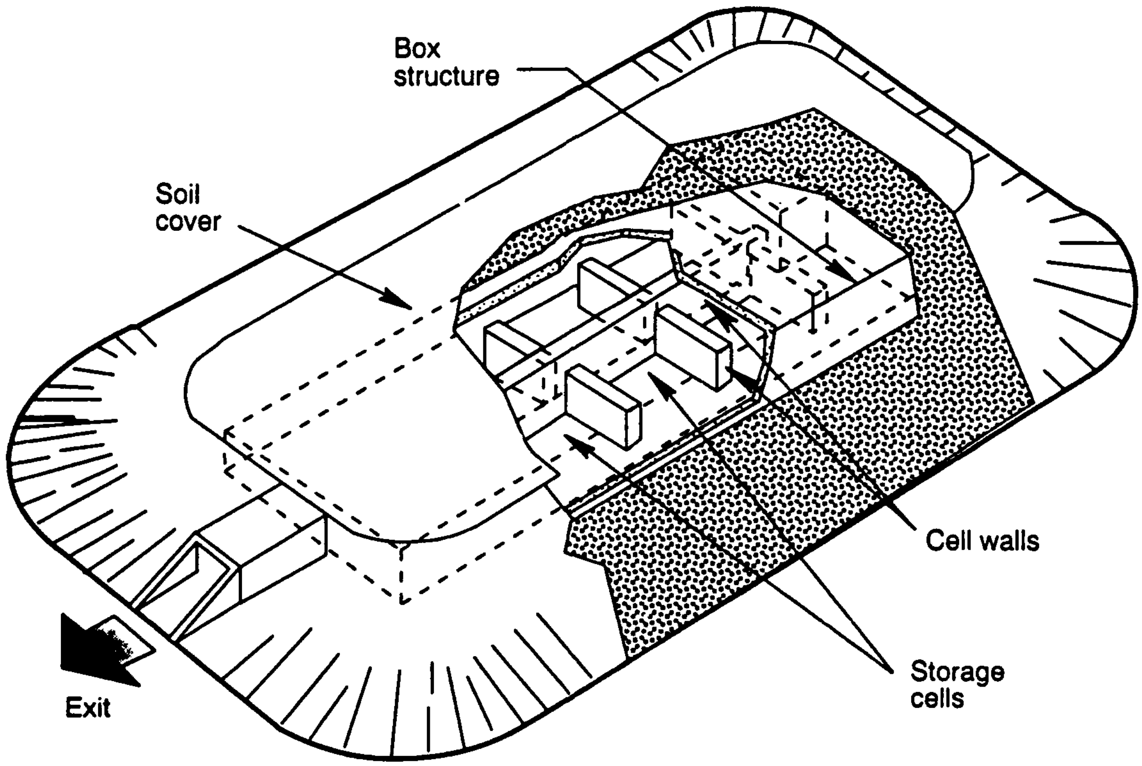

Figure 1. HP magazine concept.

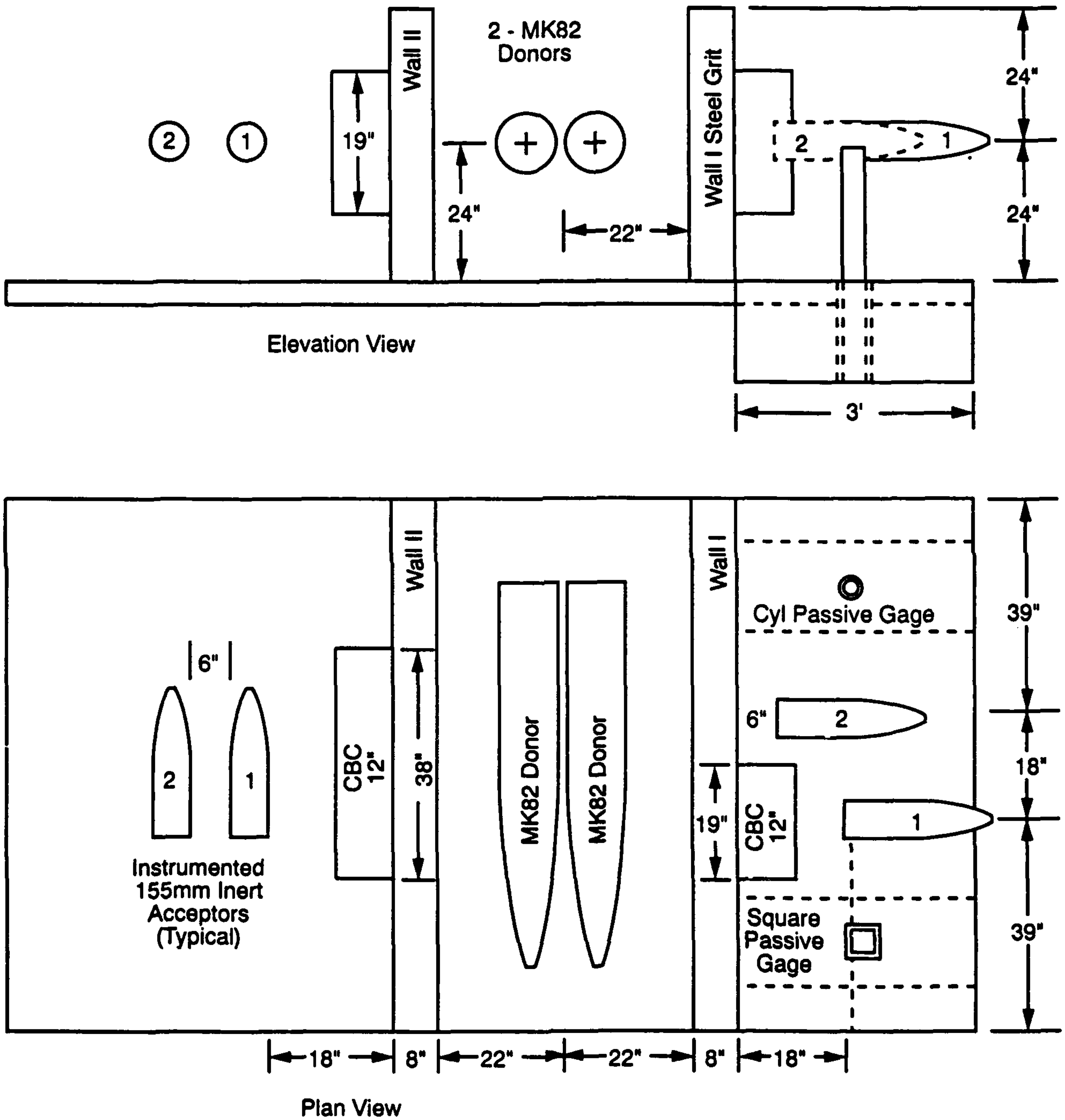

Figure 2. Typical small scale wall test setup.

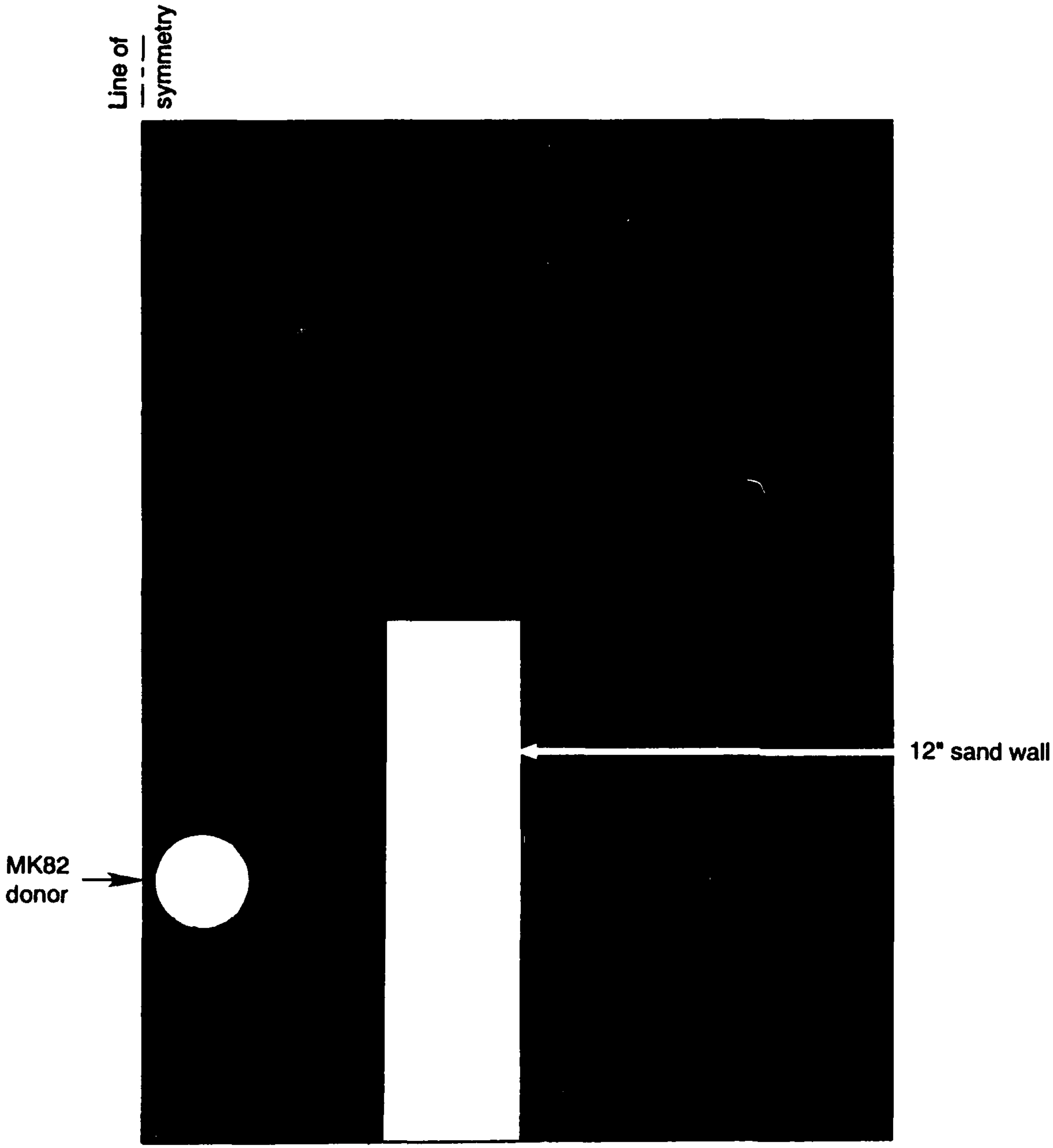

Figure 3. Two-dimensional AUTODYN model.

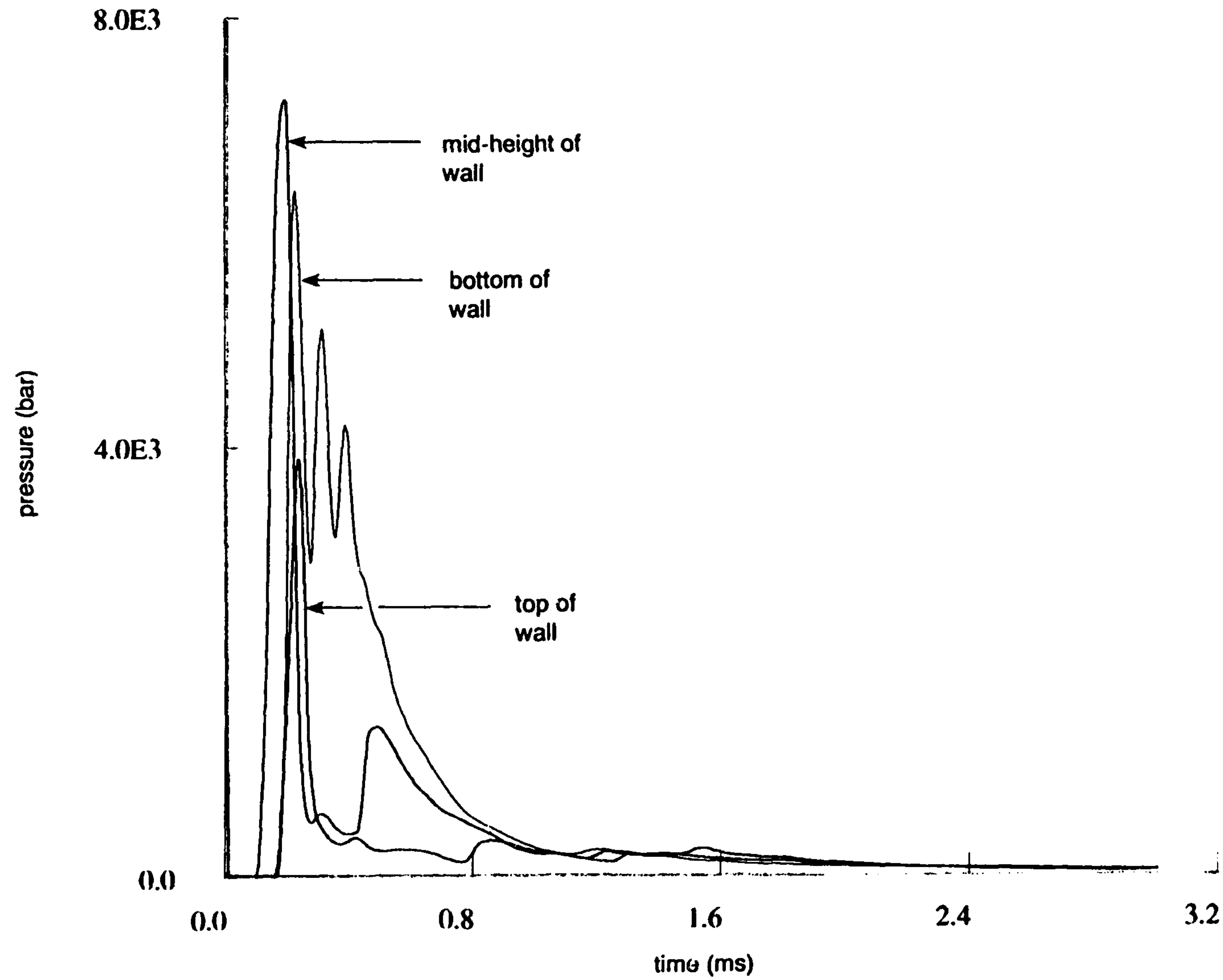

Figure 4. Pressure vs. time on donor side of wall.

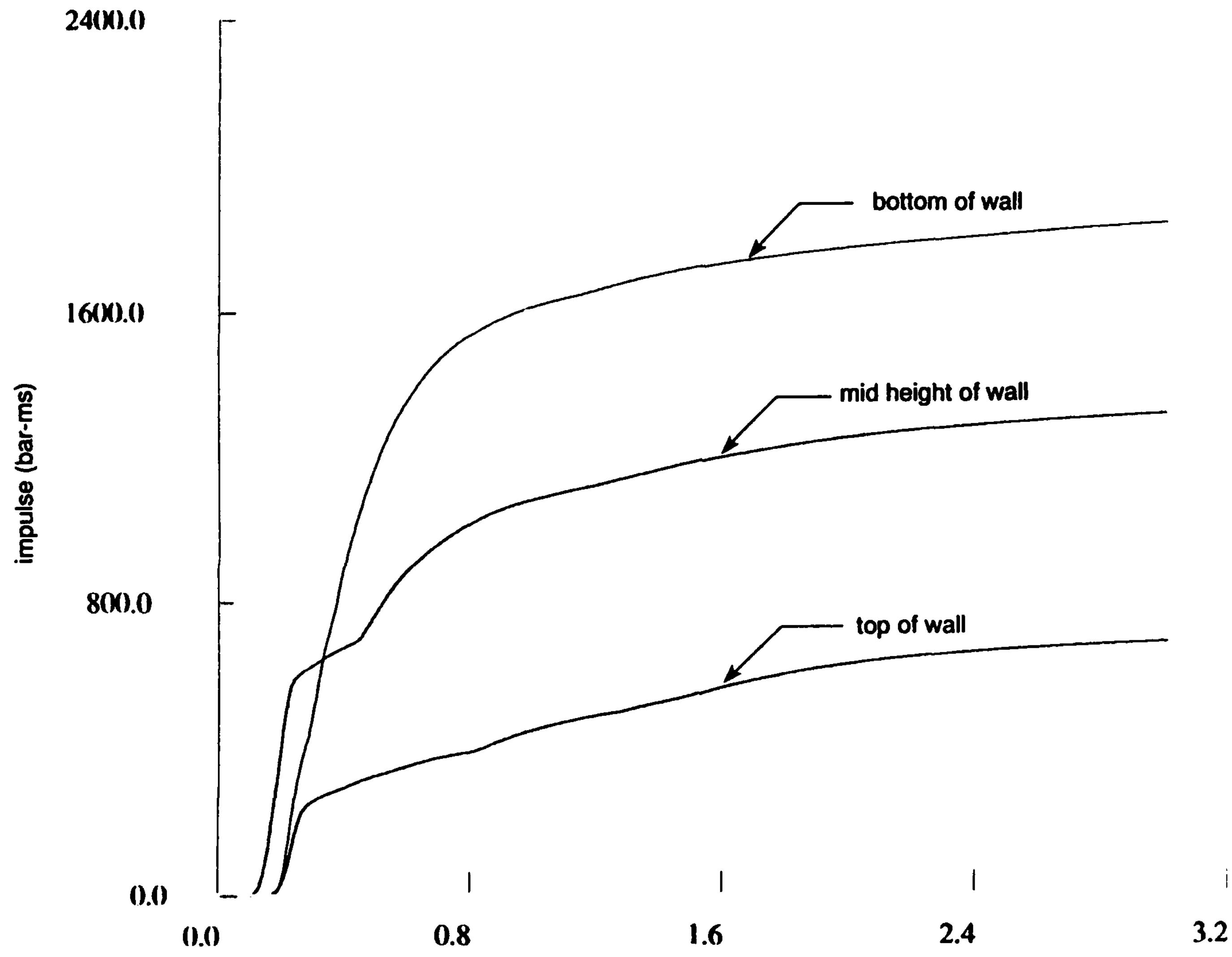

Figure 5. Impulse vs. time on donor side of wall.

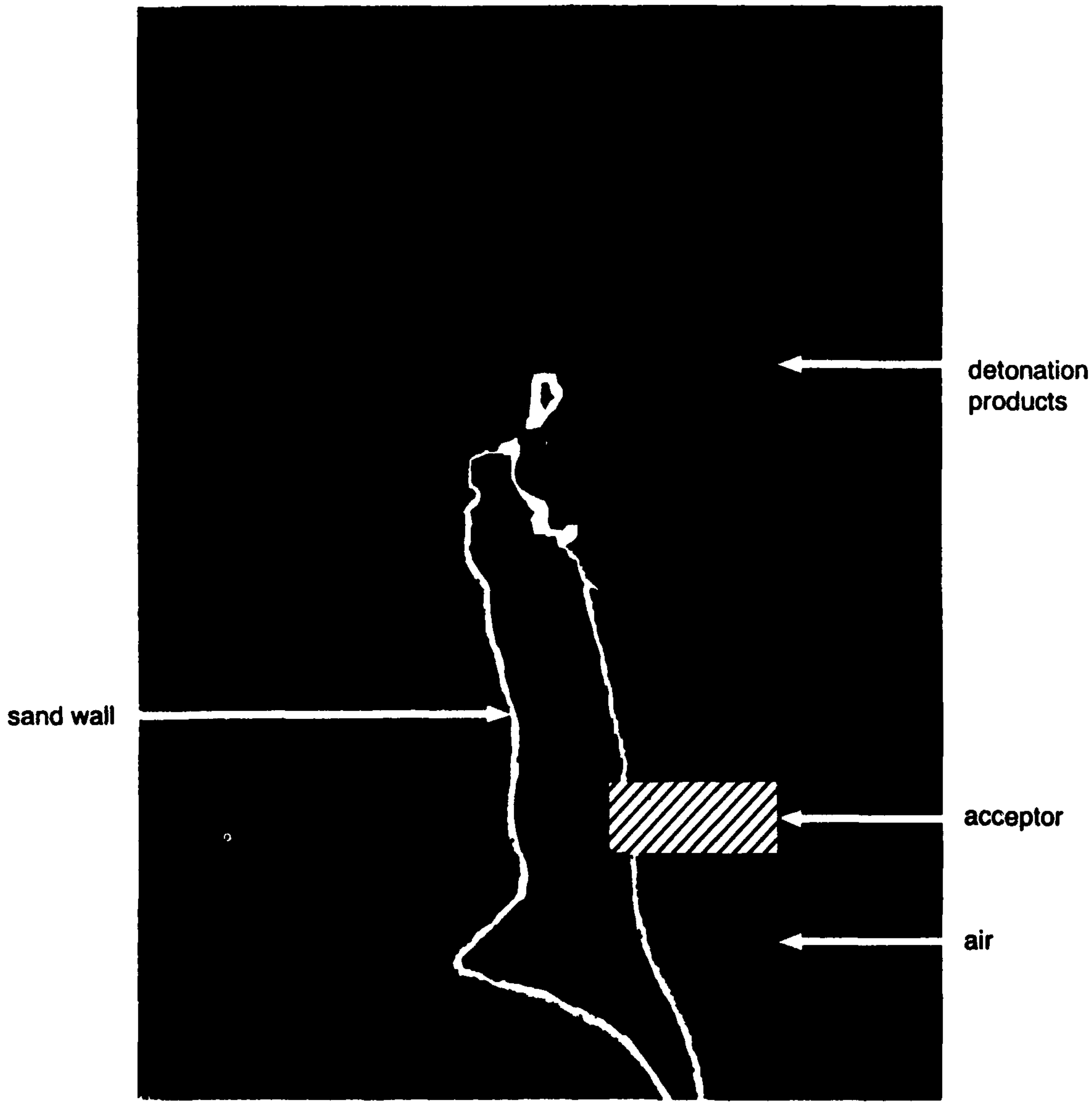

Figure 6. 12" sandwall response at T=1.59 ms.

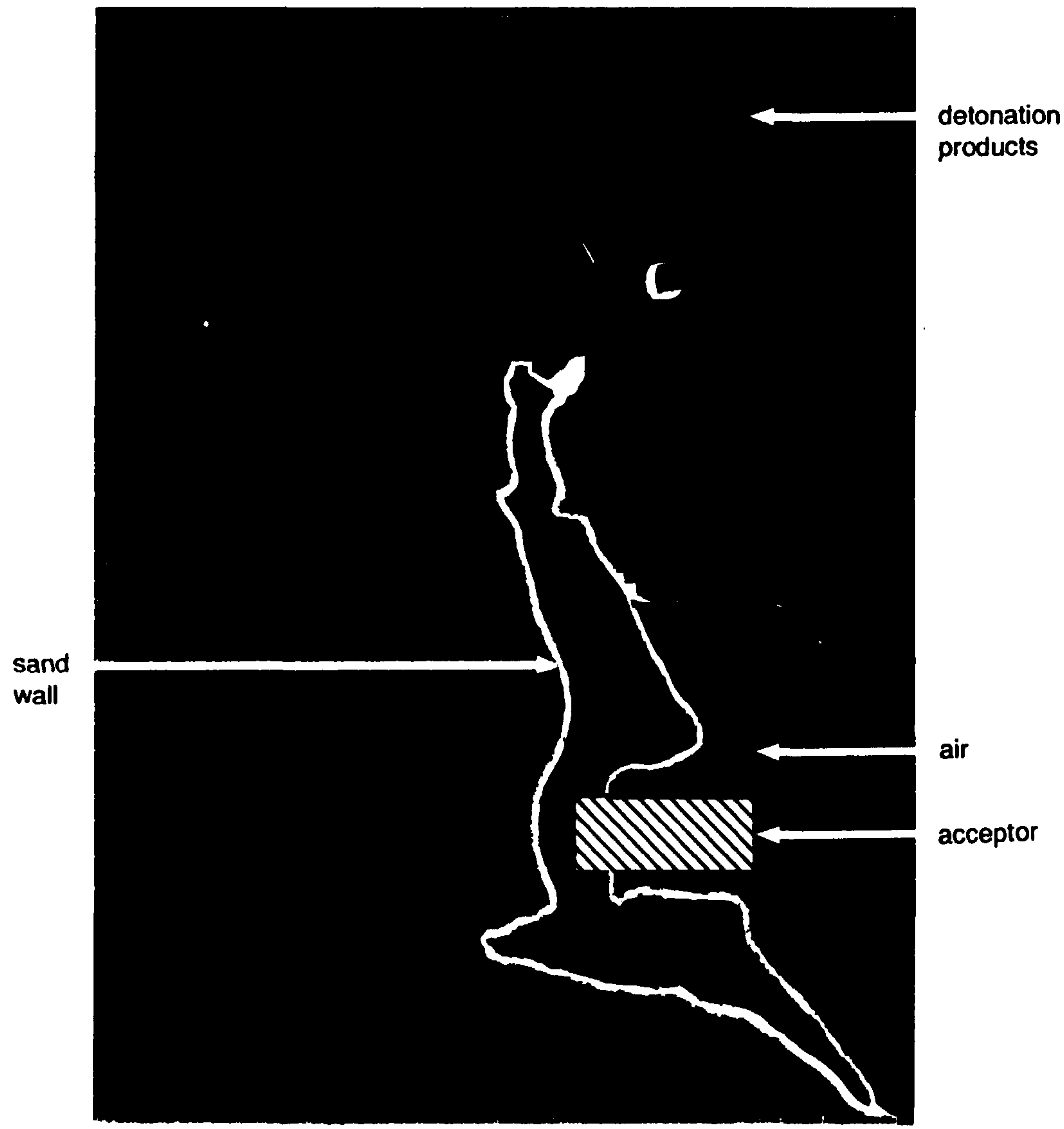

Figure 7. 12" sandwall response at T = 2.63 ms

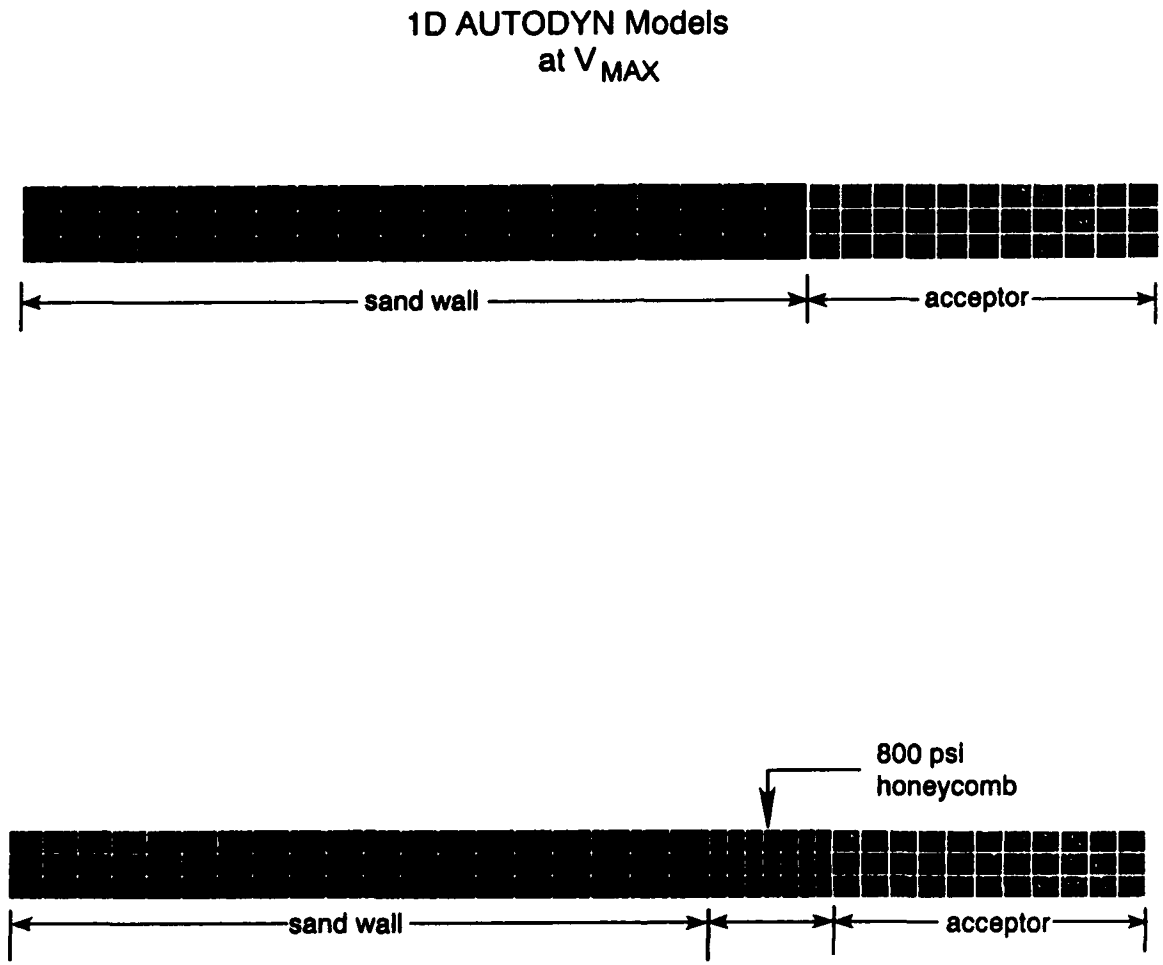

Figure 8. One-dimensional AUTODYN models.

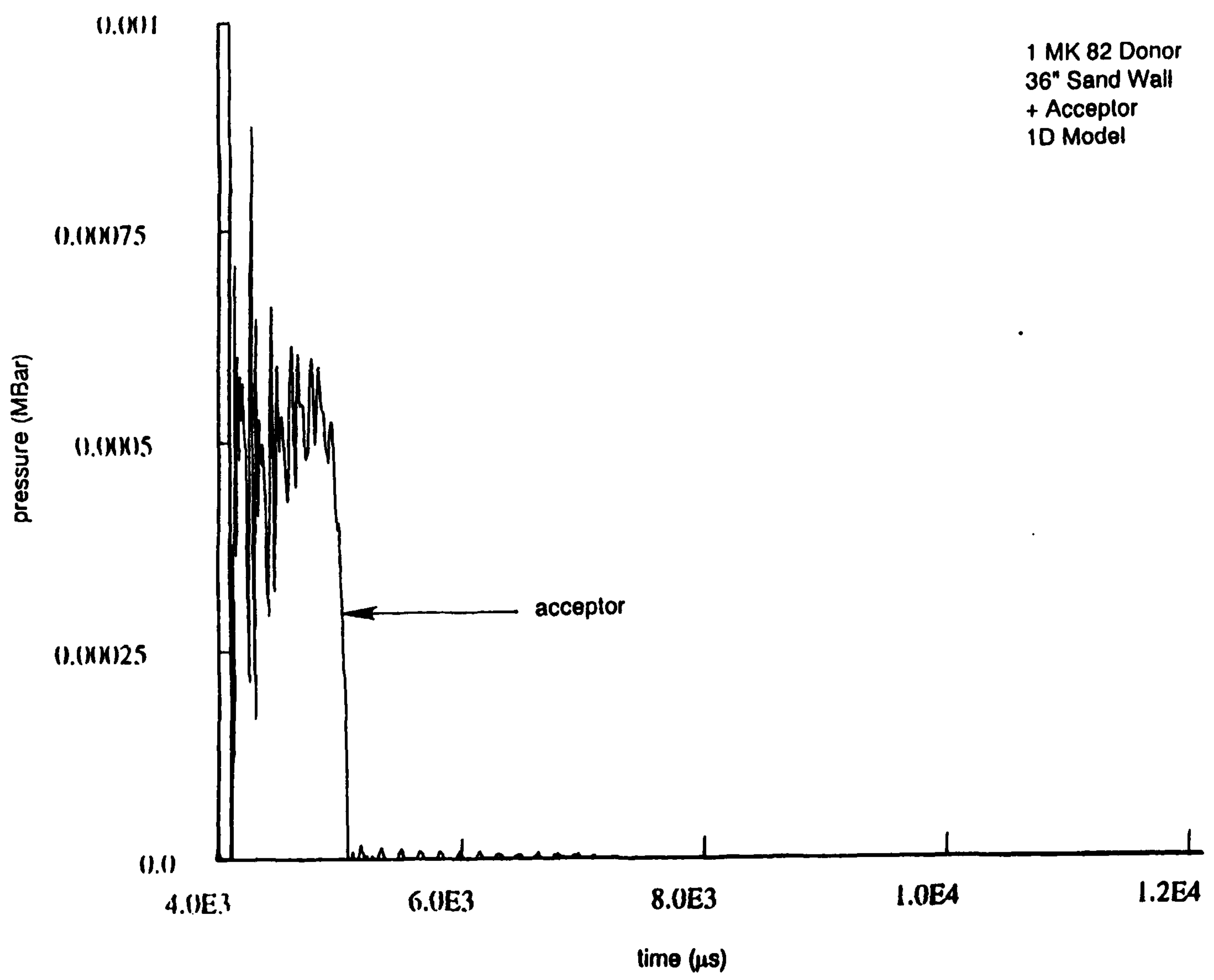

Figure 9. Pressure vs. time for acceptor opposite sand wall.

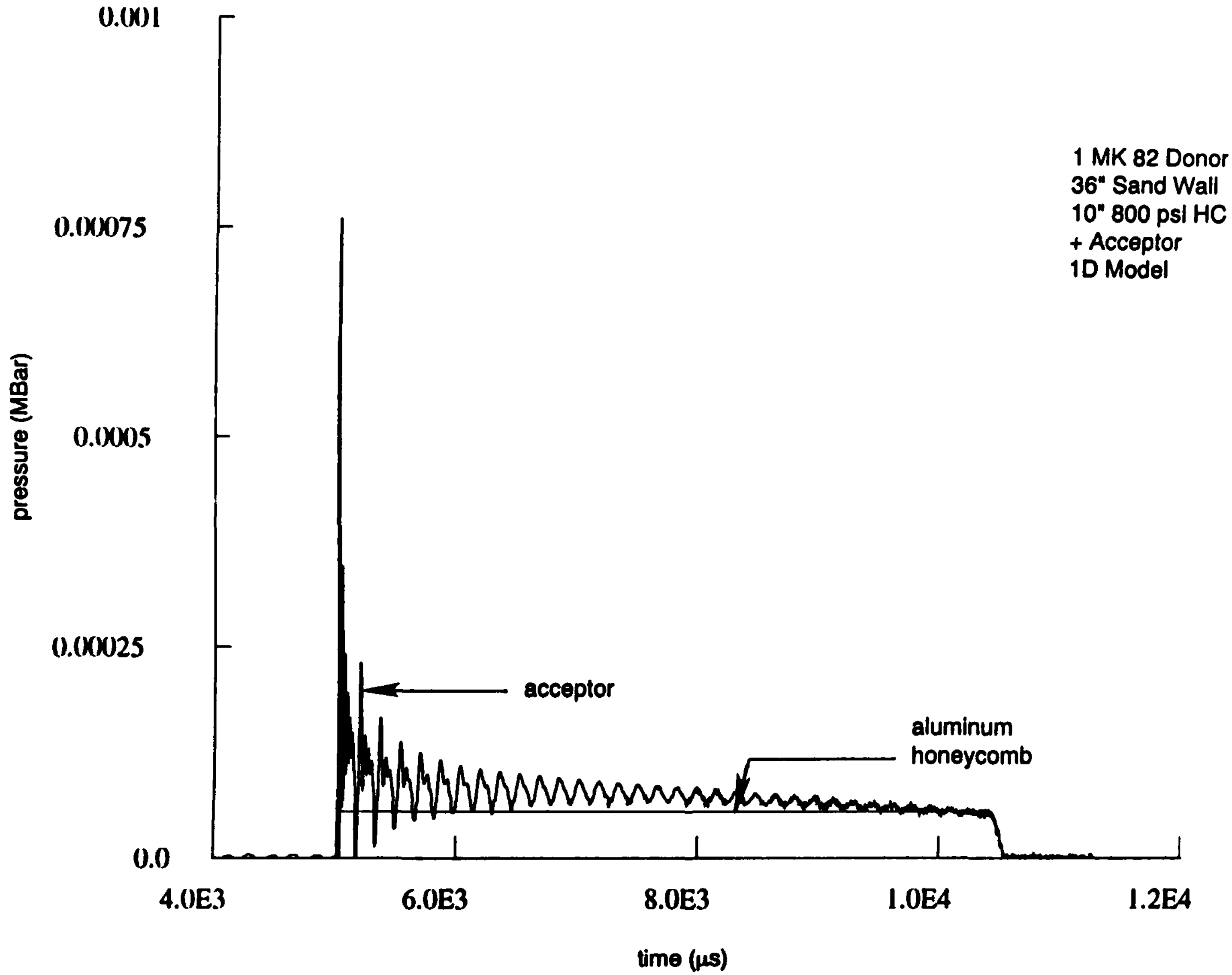

Figure 10. Pressure vs. time for acceptor opposite sand wall with 800 psi honeycomb cover.

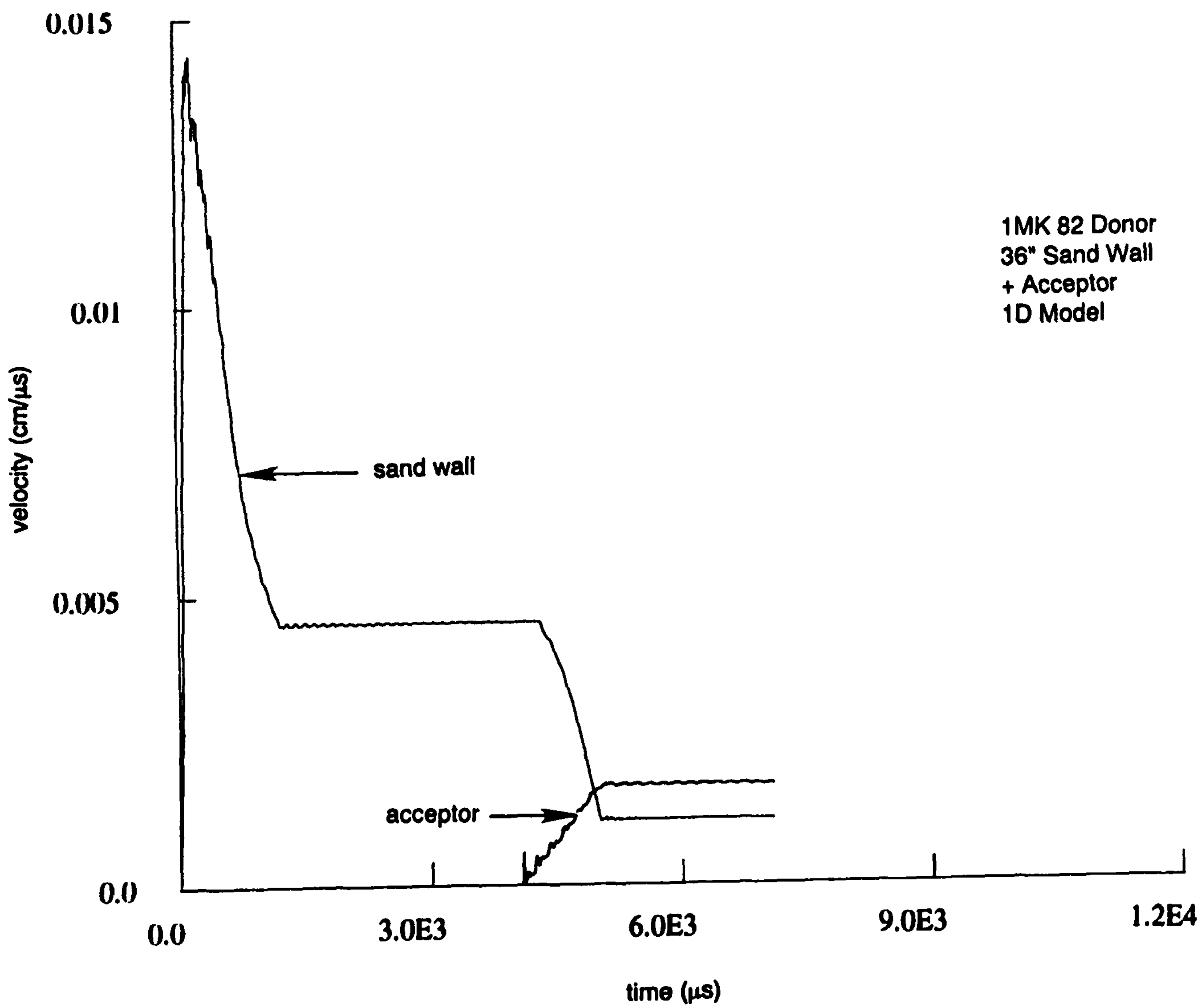

Figure 11. Velocity vs. time for sand wall and acceptor.

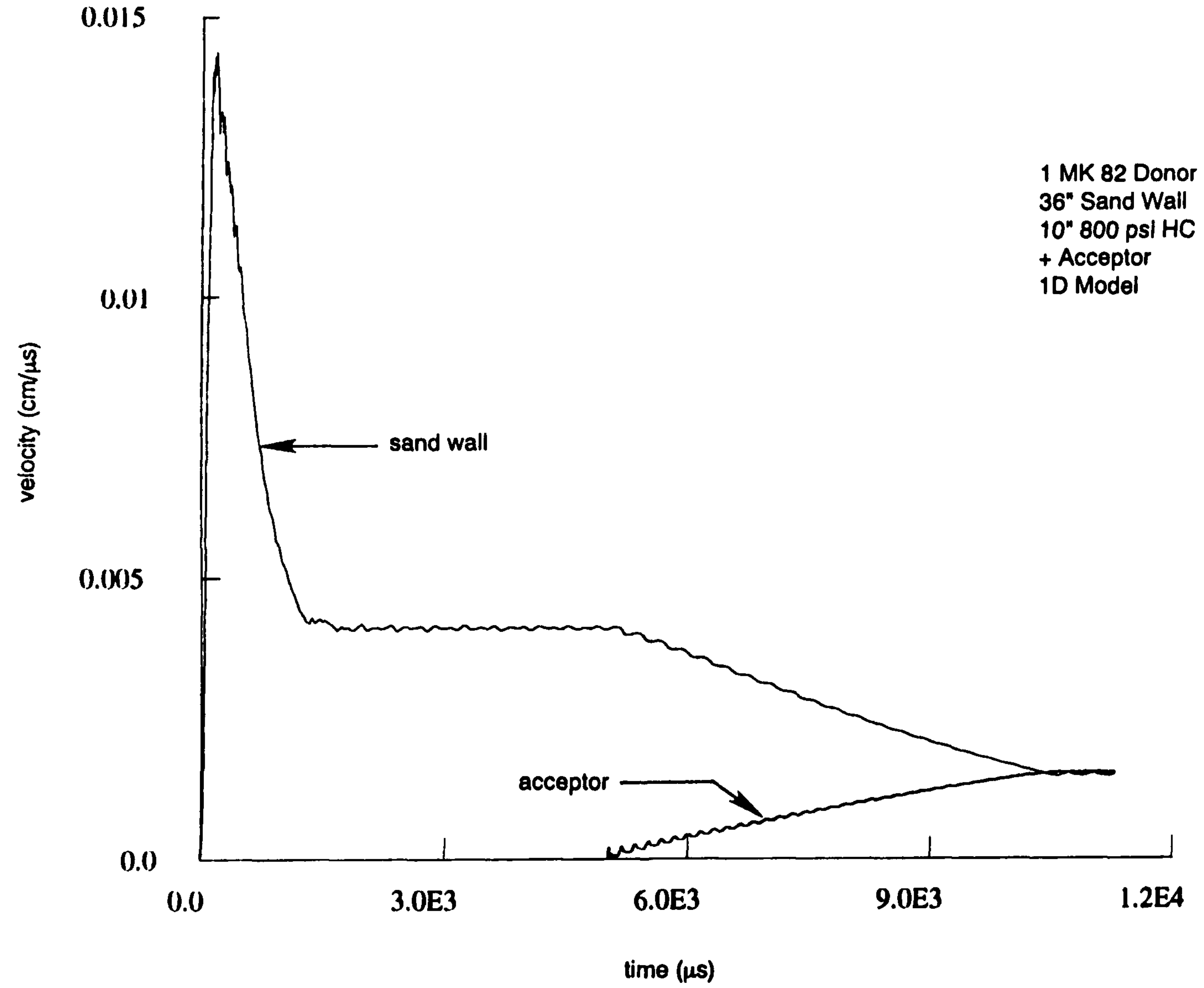

Figure 12. Velocity vs. time for sand wall (with 800 psi honeycomb cover) and acceptor.

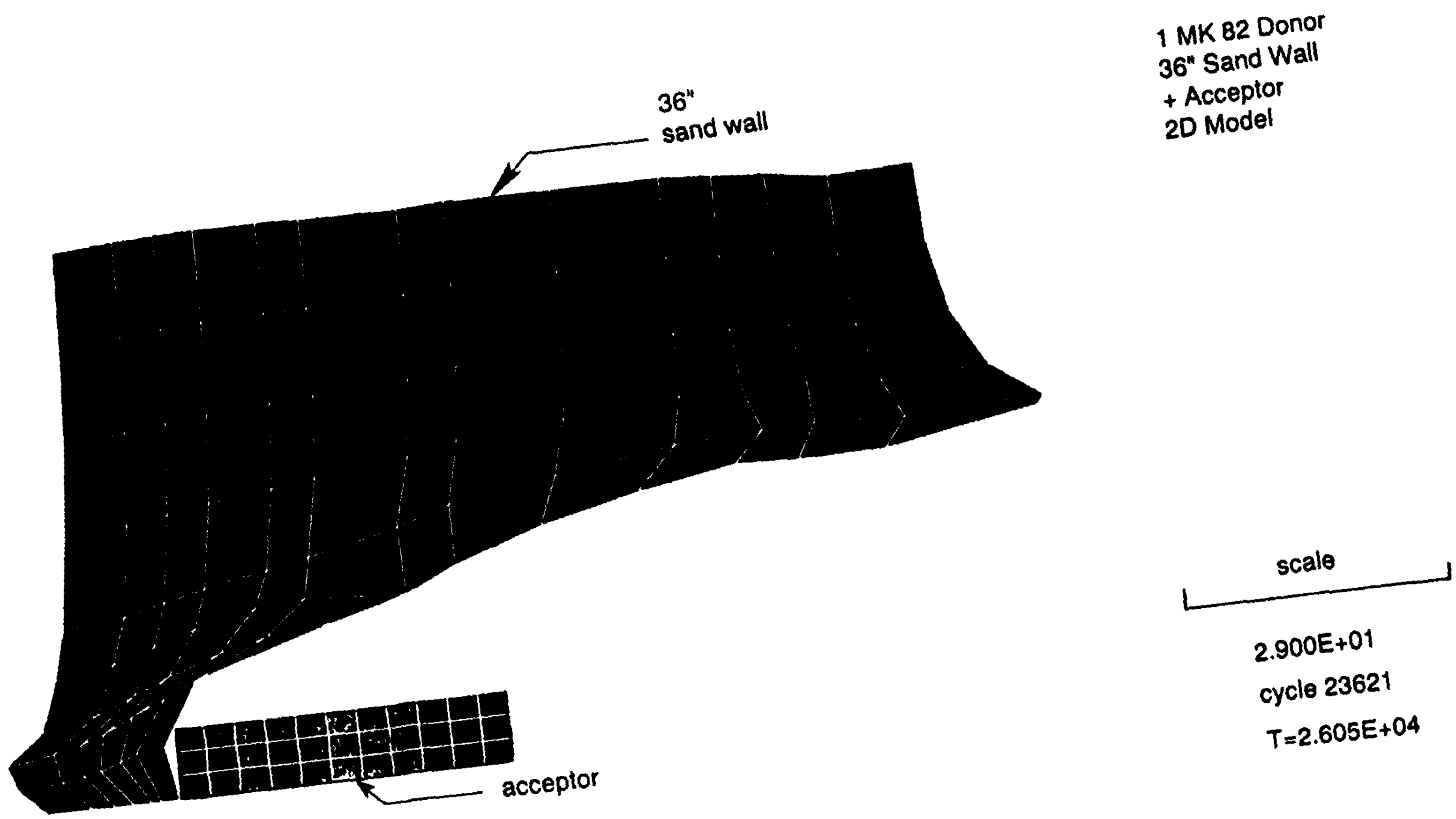

Figure 13. Two-dimensional model: sand wall and acceptor at 26 ms after impact.

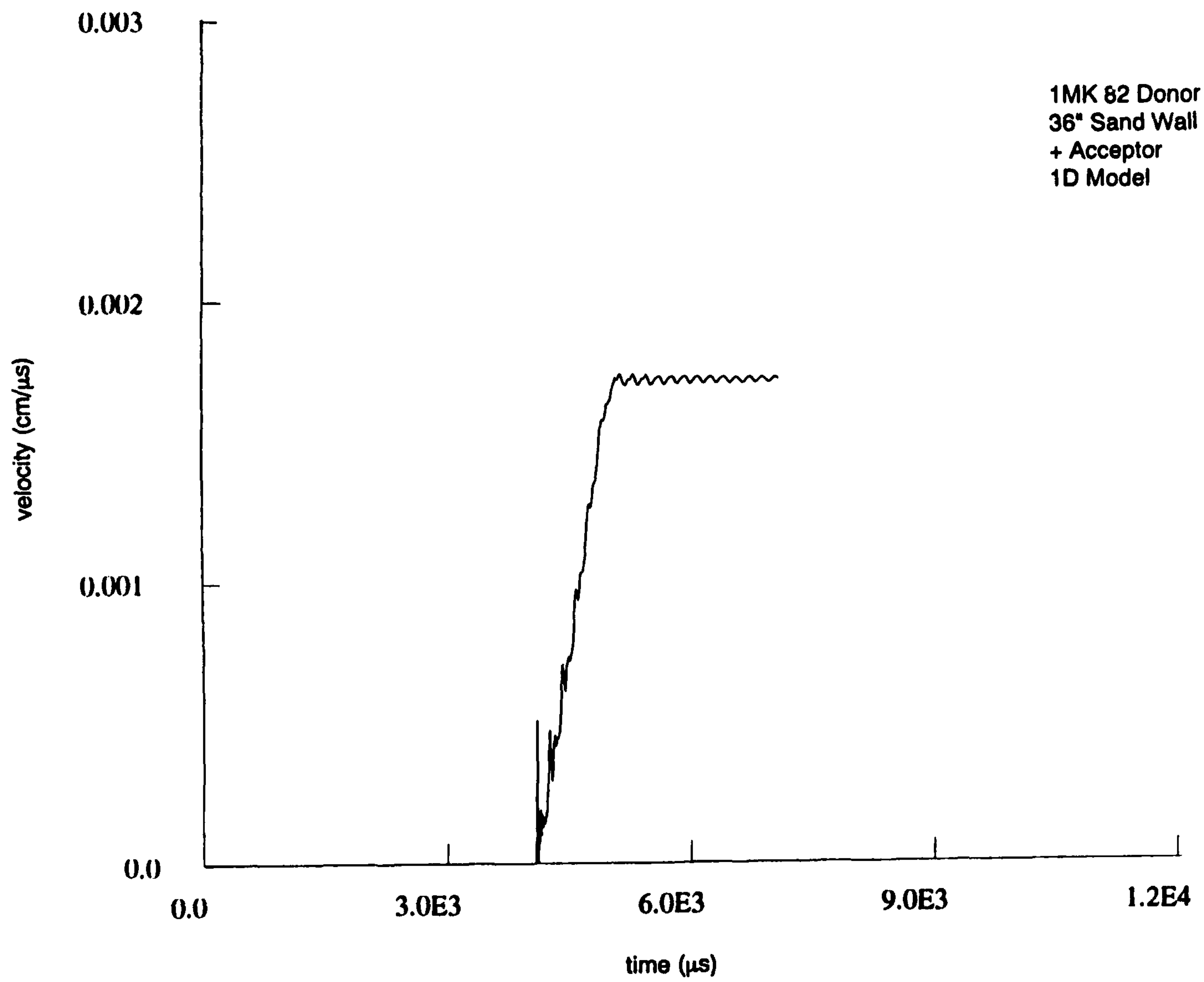

Figure 14. Acceptor velocity vs. time (sand wall - no cover).

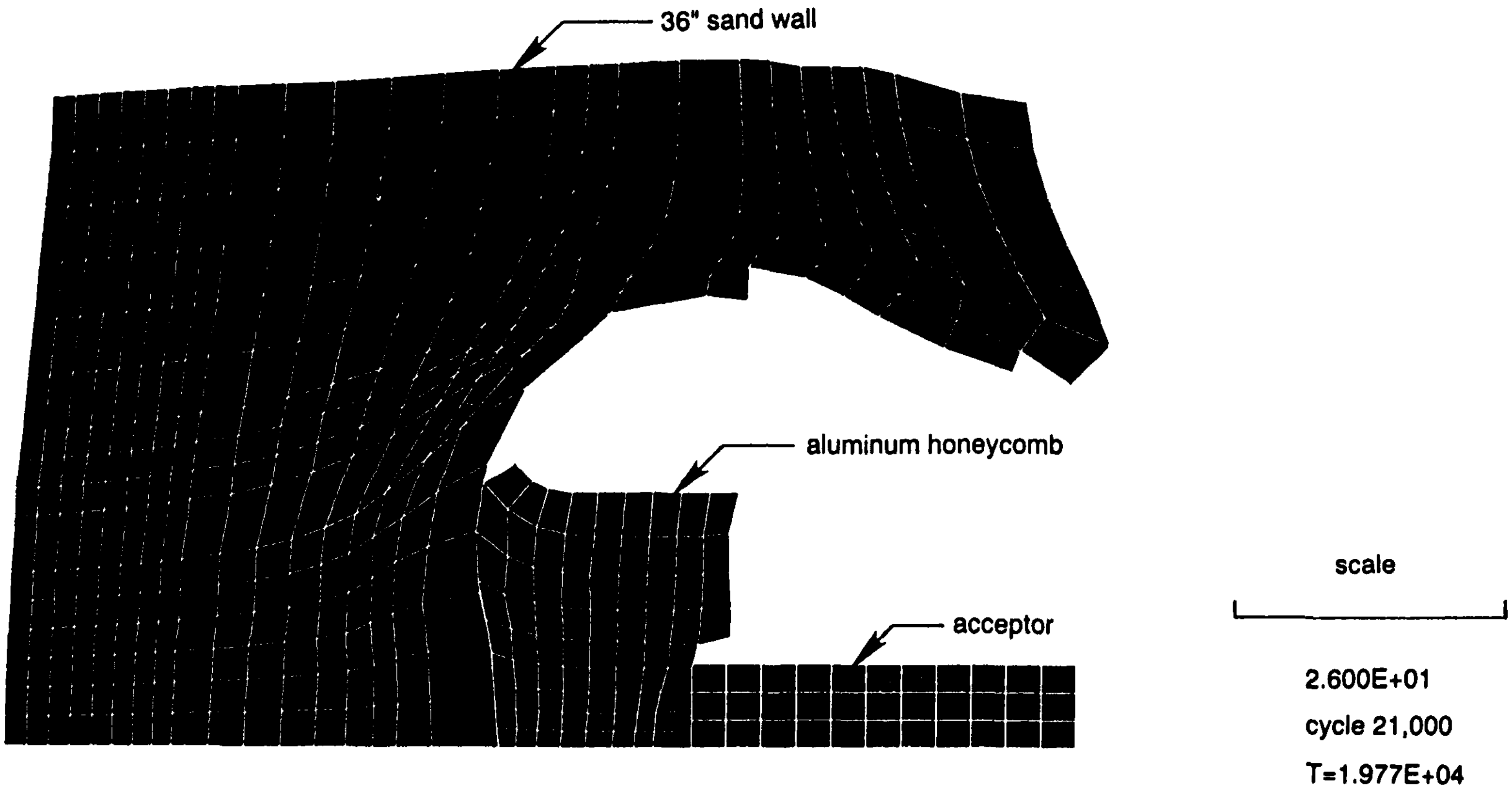

Figure 15. Two-dimensional model: sand wall, cover and acceptor at 19.8 ms after impact.

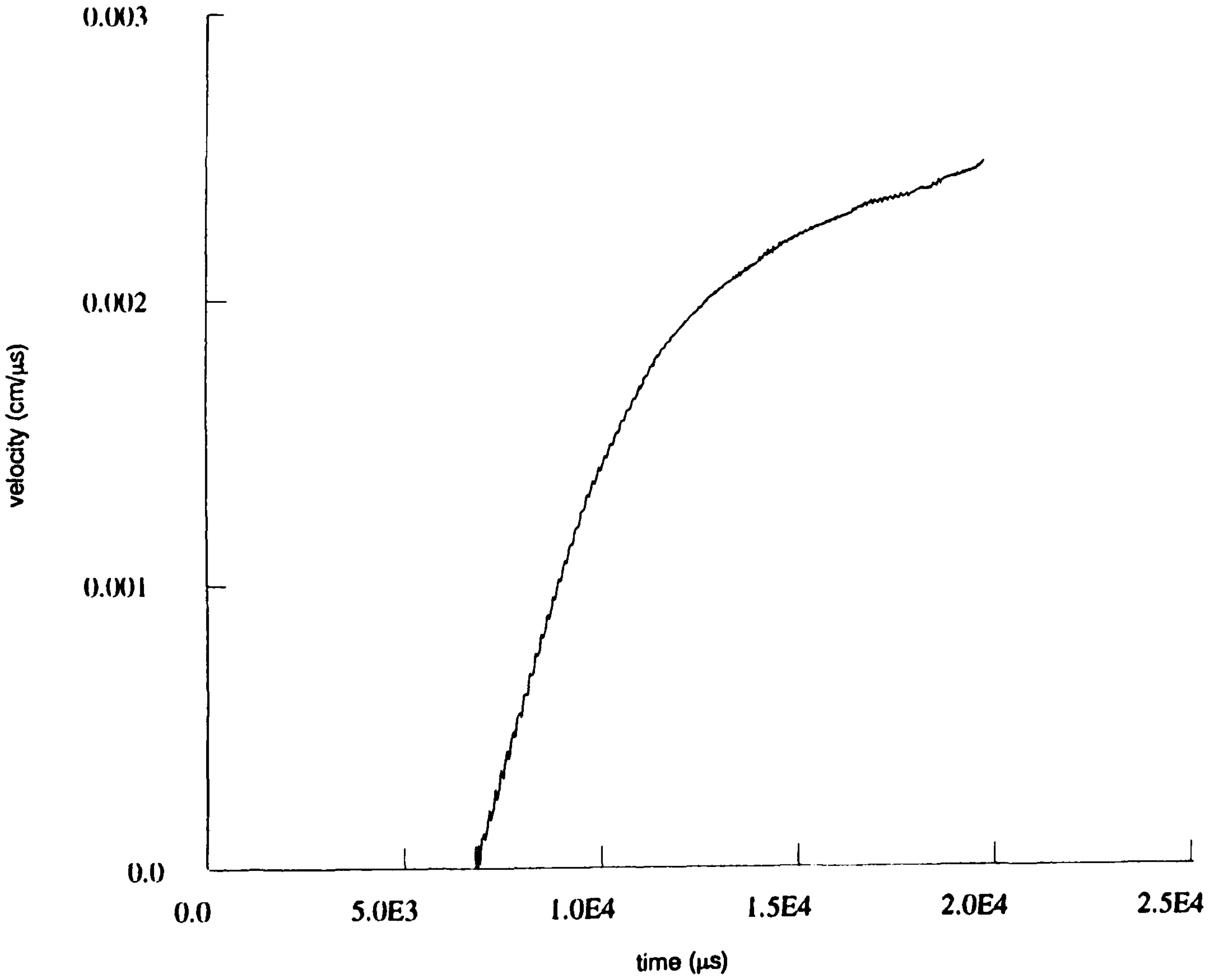

Figure 16. Acceptor velocity vs. time (sand wall with 800 psi honeycomb cover).

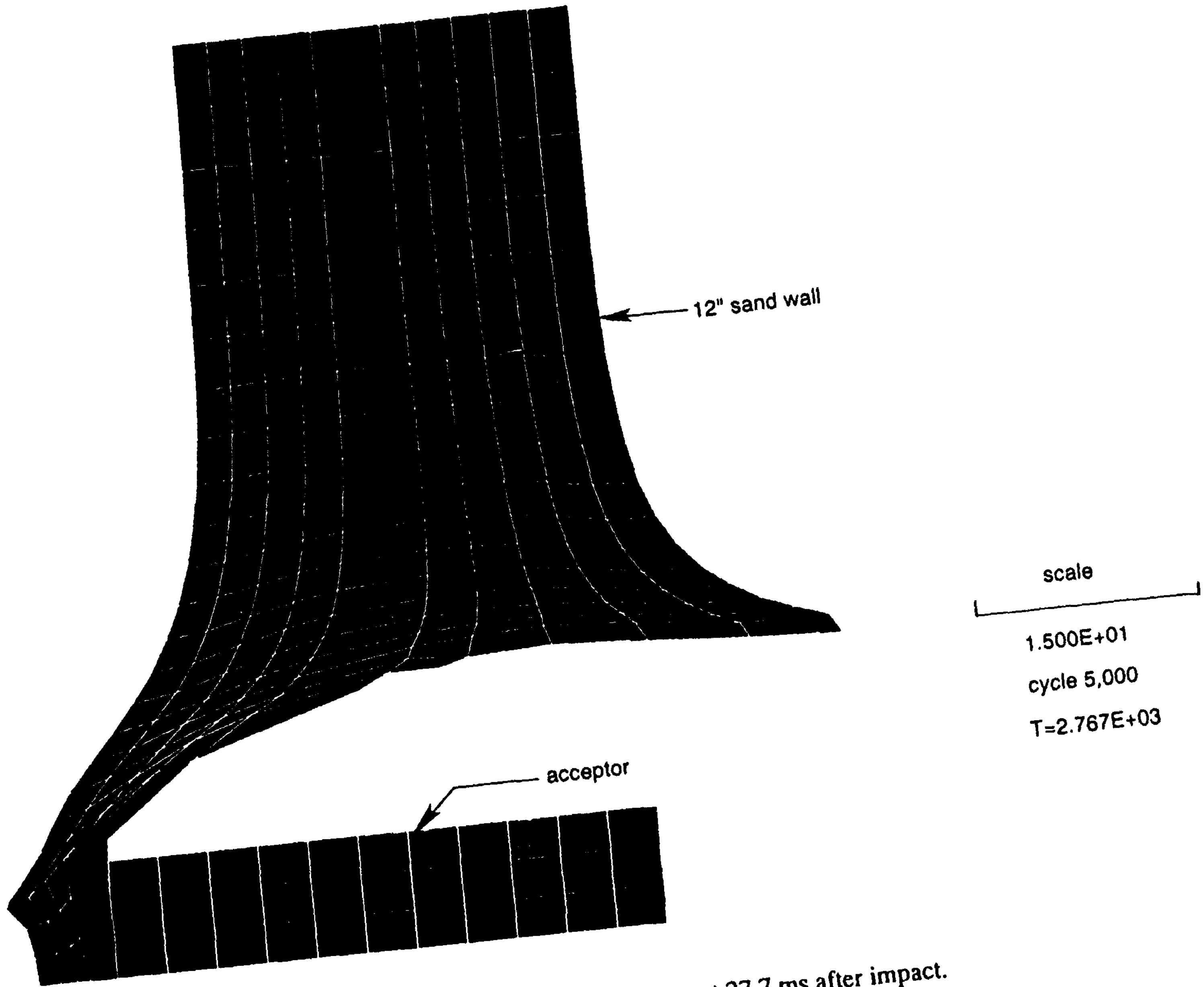

Figure 17. 12" sand wall and acceptor at 27.7 ms after impact.

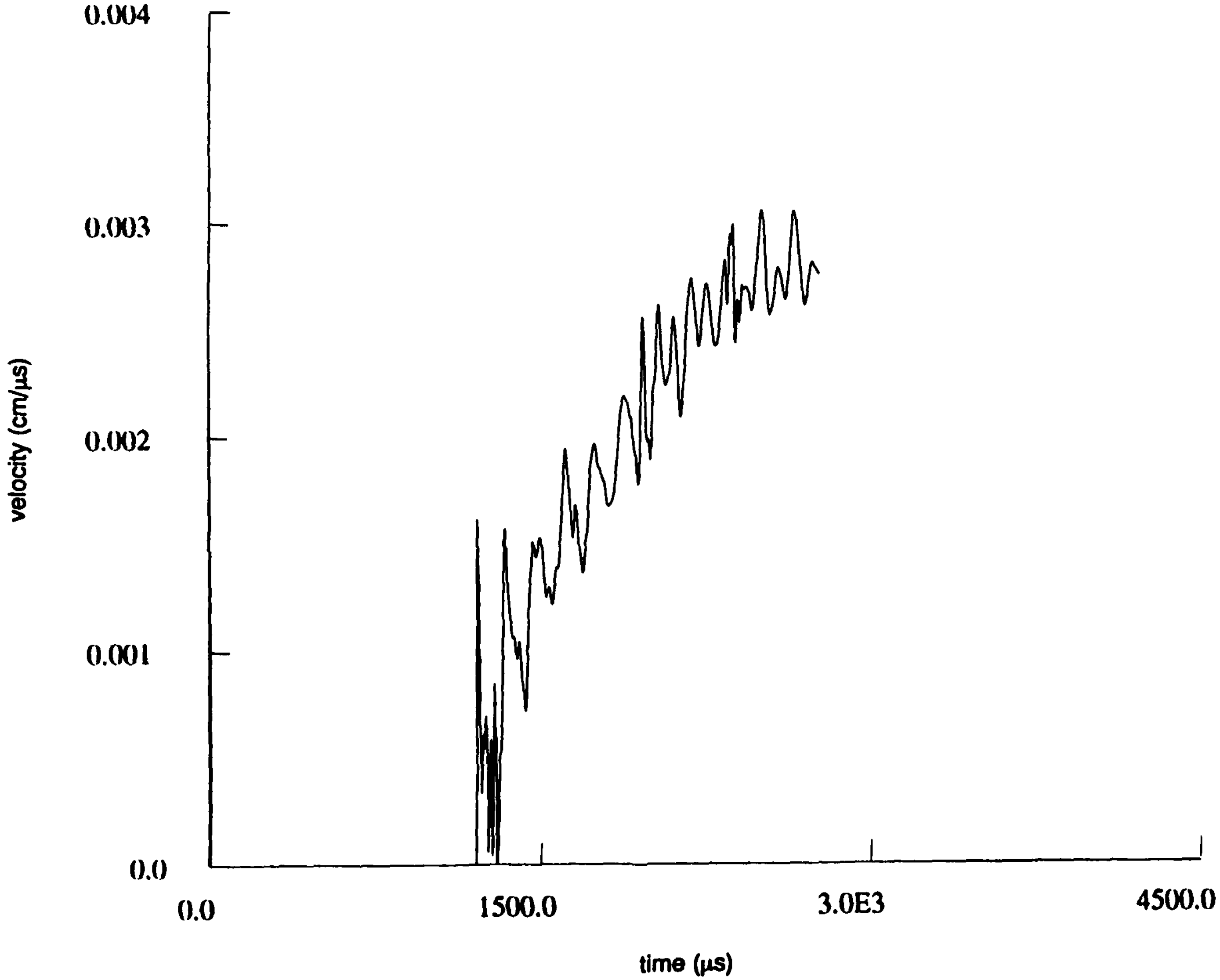

Figure 18. Acceptor velocity vs. time (12" sand wall - no cover).

SPHERICAL EQUIVALENCY OF CYLINDRICAL CHARGES IN FREE-AIR

by

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25th Department of Defense Explosives Safety Seminar
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ABSTRACT

Few experimental investigations can be found in the literature in which free-air blast parameters from cylindrical charges have been measured. As part of the work to update the DOE/TIC Manual 11268, "Prediction of Blast and Fragment Loadings on Structures," these free-air blast data were reviewed and analyzed. One of these sets of experimental data was used to develop graphs of equivalent spherical weights for cylindrical charges with length-to-diameter ratios of 1/4, 1/1, and 4/1. The actual peak side-on overpressure and impulse data from Pentolite cylindrical charges initiated at one end were scaled to standard sea level conditions using Sachs' scaling factors and the charge weights converted to equivalent TNT values based on Pentolite spherical charge test data. Then, equivalent spherical weights were determined using the standard air blast curves for spherical TNT detonations in free-air. Side-on pressure and impulse data measured along eight radials at 22.5° increments and at scaled distances of about 3 to 15ft/lb$^{1/3}$ were used to develop the equivalent spherical mass ratios. These results show the significant difference a cylindrical charge geometry has on the free-air blast loads as compared to spherical charges. To demonstrate further this difference, impulse amplitude ratios for one cylindrical charge versus a spherical charge were computed and applied to the reflected impulse loads on a flat surface from a free-air burst.

INTRODUCTION

A considerable volume of data can be found in the literature which characterize the air blast wave generated by a spherical high explosive charge detonated in free-air. For example, Goodman[1] compiled a large number of free-air measurements from spherical Pentolite experiments dating from World War II to 1960. Using these data, Goodman [1] developed a set of "standard" curves for Pentolite. Baker [2] provides an excellent historical summary of free-air measurements up to 1970. He also developed a set of standard curves for spherical charges using energy as the scaling parameter making them directly applicable to any high explosive. In 1984, Kingery and Bulmash[3] compiled experimental and computational data for TNT and Pentolite to develop an updated set of scaled standard curves for TNT spherical charges in free-air and TNT hemispherical charges on the ground. These updated curves were developed to revise the TNT standard curves in the triservice manual, Structures to Resist the Effects of Accidental Explosions [4]. Revision 1 of this manual [5] includes these curves. To apply these curves to spherical charges of explosives other than TNT, TNT equivalent weights are used.

For non-spherical free-air denotations fewer experimental studies can be found reported in the literature. For a non-spherical charge, the shock wave will not enter the surrounding air as a spherical wave, nor at the same instant over the entire charge surface. The shape and strength of the shock wave entering the air will depend both upon charge geometry, and upon the relative location at which initiation occurred. The blast parameters will be functions not only of radial standoff, but also of azimuth and possibly elevation. Several experimental programs, such as those reported in References 6 through 14, investigated the blast field around non-spherical explosives of regular geometries such as cylinders, cubes, or cones. In many instances the charges were detonated in free-air, but measurements are sometimes only of reflected parameters and along one axis.

As part of the work to update DOE/TIC Manual 11268 [15], data found in the literature from cylindrical charges were reviewed and analyzed. In Reference 15, the results of an analysis by Plooster[16] of free-air side-on pressures calculated from time-of-arrival measurements made by Wisotski and Snyer[17] and by Parks and Weeding[18] were used as a method to estimate side-on pressures from free-air cylindrical charges of three aspect ratios for a limited range of scaled distances. The results presented in Reference 16 are multi-parameter curve fits which relate the peak side-on pressure P_s to the scaled distance Z, to the length-to-diameter ratio L/D, and to the azimuth angle θ (the angle between the longitudinal axis of the cylinder and the measurement axis). These were modified slightly in Reference 15 to make them applicable to TNT charges at sea level conditions.

In the recent work at Southwest Research Institute (SwRI) to revise Reference 15, direct measurements of side-on pressure and impulse from a more recent test program of cylindrical charges conducted by Plooster[19] were found in the literature search. Reference 19 reports on the experimental measurements made from end-initiated cylindrical charges detonated in free-air. These more recent data were analyzed by SwRI to develop equivalent spherical weights for cylindrical charges with L/D of 1/4, 1/1, and 4/1. The results were included in DOE/TIC Manual 11268, Revision 1[20]. This paper will present these results as well as some of the results of additional analysis to develop pressure and impulse amplitude ratio curve fits for certain azimuth angles from a cylindrical charge with an aspect ratio of 4/1.

ANALYSIS OF CYLINDRICAL DATA

In the test program described in Reference 19, experiments were conducted with end-initiated cylindrical Pentolite charges. Pressure-time recordings were made along radials at 22.5° increments as shown in Figure 1 and at several standoff distances. Most of the tests used cast Pentolite, 8 lb cylindrical charges with a few 16 lb charges also being fired. Some tests using 8 lb Pentolite spheres were fired throughout the program for internal calibration purposes. The test arena was laid out with two radial lines of side-on pressure transducers (6 sensors per line) placed 90° apart. Thus, each test generated pressure-time histories at two angles. The cylindrical charges were fired with their axes horizontal as indicated in Figure 1 and 12 ft above the ground to minimize ground reflections from interfering with the initial blast wave at the transducer locations. The pencil gages were also mounted at an elevation of 12 ft and at radial distances ranging from 7 to 31 ft. To obtain data at 22.5° intervals, the cylindrical charge was rotated relative to the two orthogonal transducer radials from test to test. Thus, data were obtained at each angle of interest in 5 tests.

Pentolite cylindrical charges of seven L/D ratios were used. However, measurements were made at all nine of the 22.5° intervals and in multiple firings only for charges with L/D ratios of 1/4, 1/1, and 4/1. Consequently, the analyses performed in rewriting Reference 15, and in writing this paper, used data only from tests using these 3 aspect ratios. Tabulations of the peak pressure P_s and positive impulse i_s data as measured at an average ambient pressure of 11.9 psia are presented in Reference 19. These data are also plotted in that reference scaled to a charge weight of one pound and to sea-level ambient pressure as a function of L/D for different scaled distances for a particular azimuth angle θ, and as a function of θ for different scaled distances for a particular L/D. Note that since cylindrical charges often generate secondary shock waves which are comparable or of greater amplitude than the leading shock, the pressure data tabulated in Reference 19 include any such significant peak pressures.

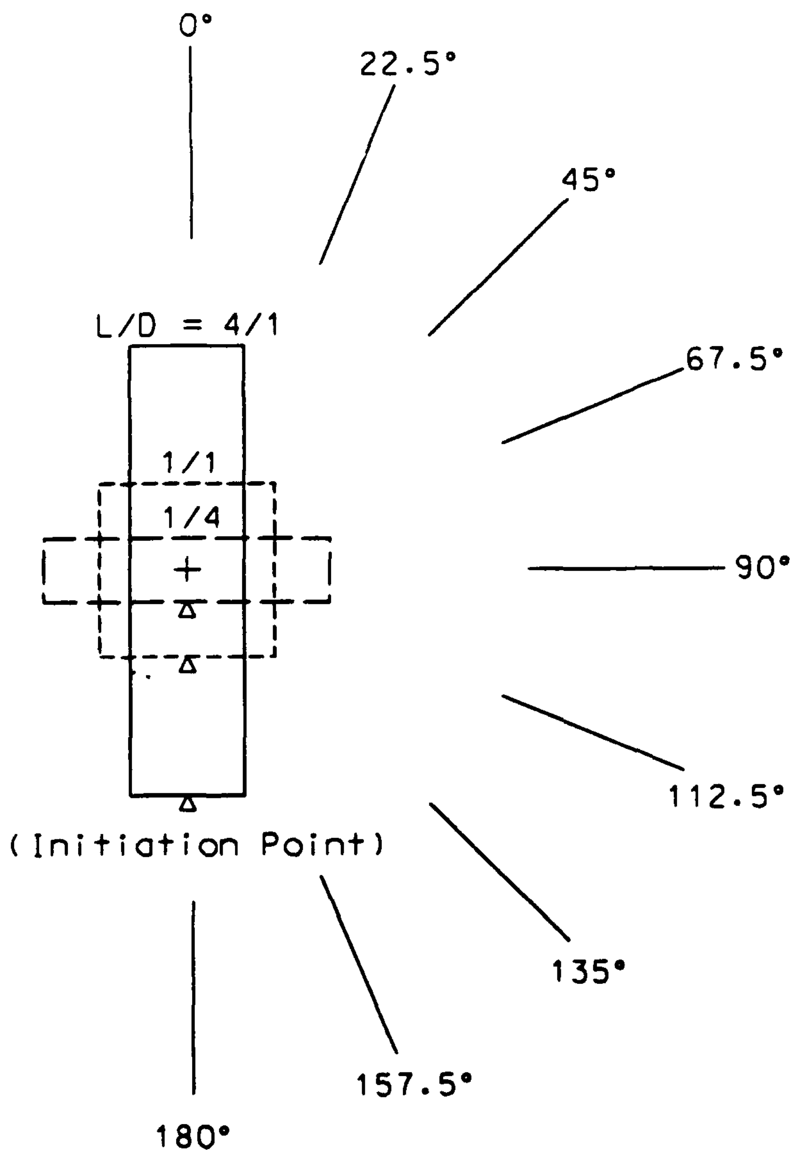

Figure 1. Plan View of Measurement Lines for a Free-Air Cylindrical Charge

To provide structural designers using Reference 20 with at least approximate correction factors to account for cylindrical charge geometry in determining blast loads, the data from Reference 19 were used to develop graphs of equivalent spherical weights as a function of scaled distance for each azimuth angle and aspect ratio. The side-on pressure and impulse data from Reference 19 for 8-lb Pentolite, free-air cylinders with aspect ratios of 1/4, 1/1, and 4/1 were first adjusted to standard sea-level ambient pressure using Sachs' scaling factors as discussed in Reference 20. The same scaling was also applied to the spherical free-air data recorded throughout the test program described in Reference 19.

Since the experiments were performed with Pentolite charges, the next step in standardizing the data was to convert them to TNT equivalent data. Separate TNT equivalency adjustments were made to the pressure data and to the positive impulse data. TNT equivalency is defined as the ratio of the charge weight of TNT to the weight of the high explosive in question that will yield the same amplitude of a blast parameter at the same radial distance from each charge.

The average pressure or impulse measured on the spherical tests at each of the six scaled distances was used to determine a TNT equivalency for each blast parameter using the standard free-air TNT curve developed by Kingery and Bulmash[3]. The average pressure or impulse at each scaled distance was determined from as many as ten measurements. The equivalency factors at the six scaled distances ranging from about 3 to 15 $ft/lb^{1/3}$ (corrected to sea-level) were then averaged to obtain one value for pressure and one value for impulse which was then applied to the cylindrical data. The average TNT equivalency factor based on the side-on pressure data from the spherical charges was determined to be 1.08. The average TNT equivalency factor based on side-on impulse was 0.9. With these factors, TNT scaled distances for the side-on pressures, and TNT scaled impulses and their corresponding scaled distances were computed from the cylindrical test data already corrected to sea-level conditions.

SPHERICAL EQUIVALENCY FACTORS

With the cylindrical data from Reference 19 scaled to sea-level ambient pressure and in equivalent TNT form, the standard TNT curves were used as the basis for computing spherical equivalency factors. Figure 2 shows one example of a comparison between the side-on pressures from a cylindrical charge of L/D = 4/1 measured at azimuth angles of 22.5°, 45°, 67.5°, and 90° and the spherical TNT curve.

The spherical equivalency factors were determined in a similar way as TNT equivalency weights are generally found. For each cylindrical side-on pressure or impulse data point, an

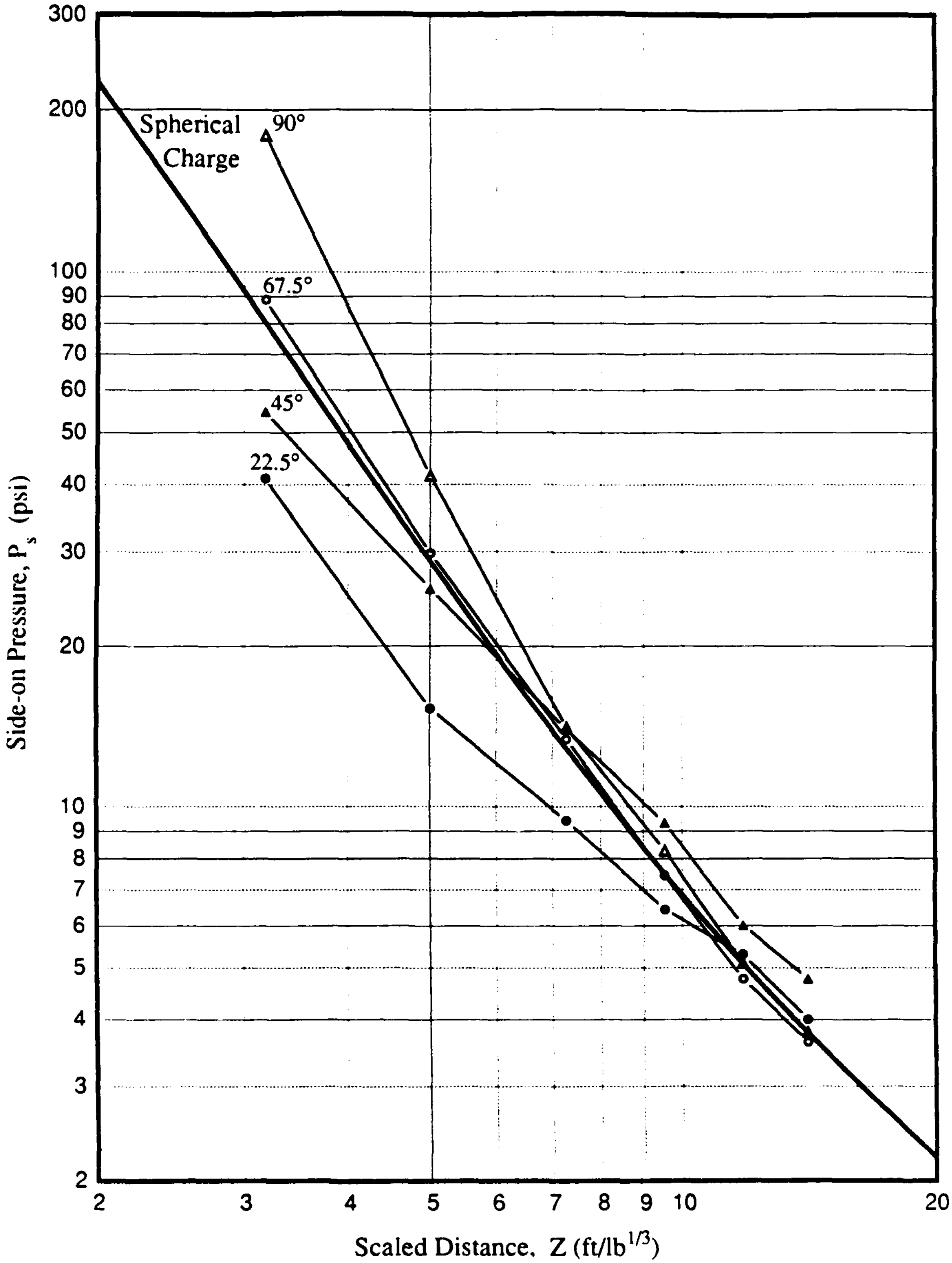

Figure 2. Side-on Pressure Data from a TNT Cylindrical Charge of L/D = 4/1 Compared to TNT Spherical Curve

equivalent spherical weight was determined that would produce the same side-on pressure or impulse at the same distance, R. Thus, for side-on pressure, the ratio of the charge weight of a sphere W_{sph} to that of a cylinder W_{cyl} is

$$\frac{W_{sph}}{W_{cyl}} = \left(\frac{Z_{cyl}}{Z_{sph}}\right)^3_{P_s\,=\,\text{constant}} \qquad (1)$$

likewise, for side-on impulse

$$\frac{W_{sph}}{W_{cyl}} = \left(\frac{Z_{cyl}}{Z_{sph}}\right)^3_{i_s\,=\,\text{constant}} \qquad (2)$$

In these equations, Z_{cyl} is the scaled distance $R/W_{cyl}^{1/3}$ and Z_{sph} is the scaled distance $R/W_{sph}^{1/3}$.

Equivalent spherical mass ratios for cylindrical charges with an aspect ratio of 1/4, 1/1, and 4/1 based on side-on pressure measurements at different azimuth angles are presented in Figures 3 through 7. A similar set of ratios based on side-on impulse data are presented in Figures 8 through 12. As mentioned before, the cylindrical charges were initiated at the 180° end (see Figure 1). Consequently, the data is somewhat unsymmetric about the 90° line. For example, Figure 13 shows the pressure-based equivalency factors for a cylinder with L/D = 4/1 at all the azimuth angles. If a cylindrical charge was to be initiated at the longitudinal center, one would expect similar blast load amplitudes at symmetric angles about the 90° radial, such as 0° and 180°, 45° and 135°, etc. Therefore, to apply the end-initiated cylindrical data to a centrally initiated cylinder, the results in Figures 3 through 12 may be used for angles of 0° to 90° and assume the same amplitudes for corresponding angles greater than 90° up to 180°.

BLAST LOADS FROM A CYLINDRICAL CHARGE

In Reference 20, simple examples are used to show how the data presented in Figures 3 through 12 can be used to determine side-on pressures from a cylindrical charge. In one example, the side-on pressures generated by a cylindrical charge of L/D = 1/1 and a TNT equivalent weight of 57.4 lb are estimated at a standoff distance R of 25 ft and azimuth angles θ of 0°, 45° and 90°. Using Figures 3, 4, and 6 to find the equivalent spherical weight at each angle, and the standard TNT free-air curve for a spherical charge in Reference 20 to find the corresponding pressure, the results were as follows:

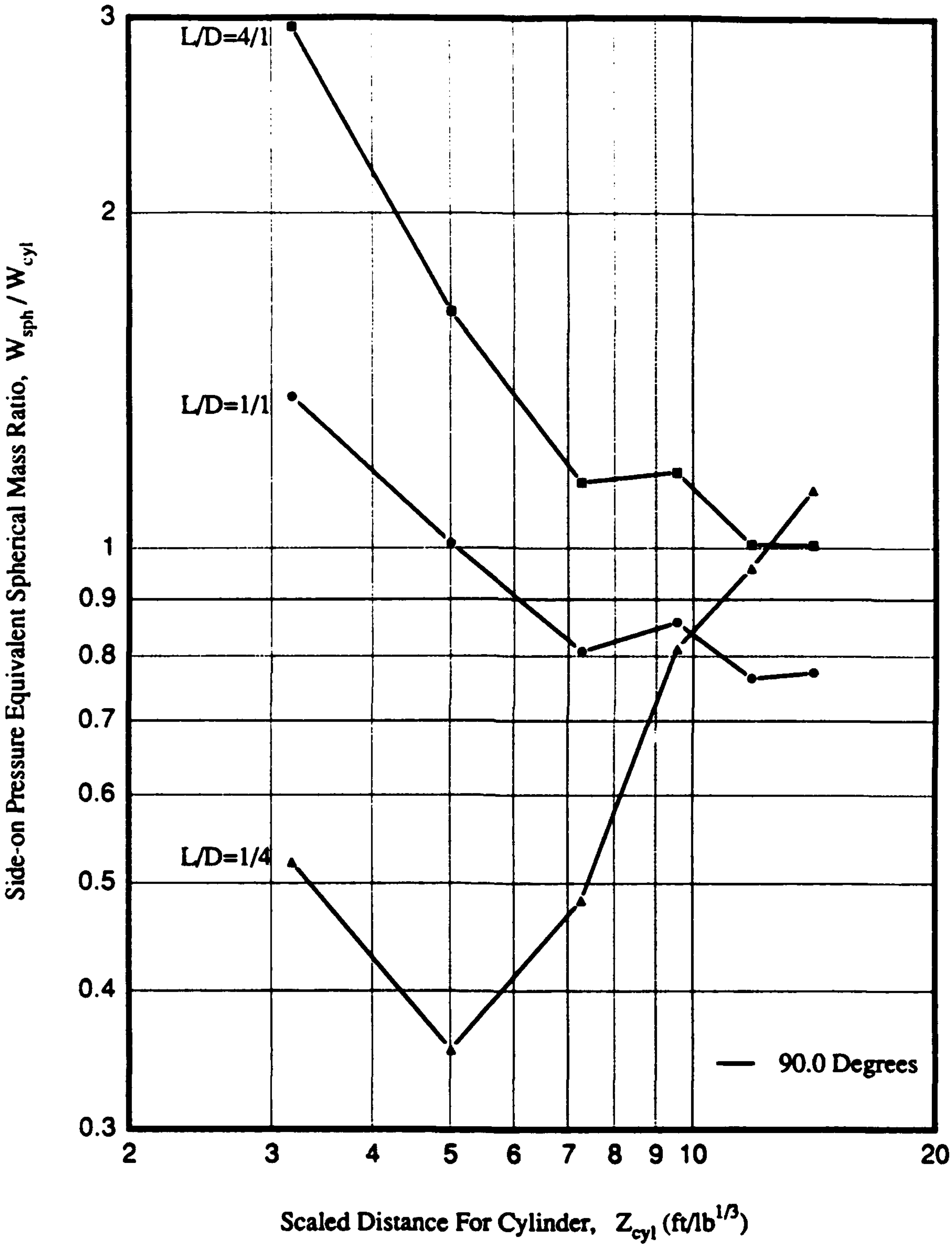

Figure 3. Equivalent Spherical Mass Ratio Based on Experimental Side-on Pressures at an Azimuth Angles of 90° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

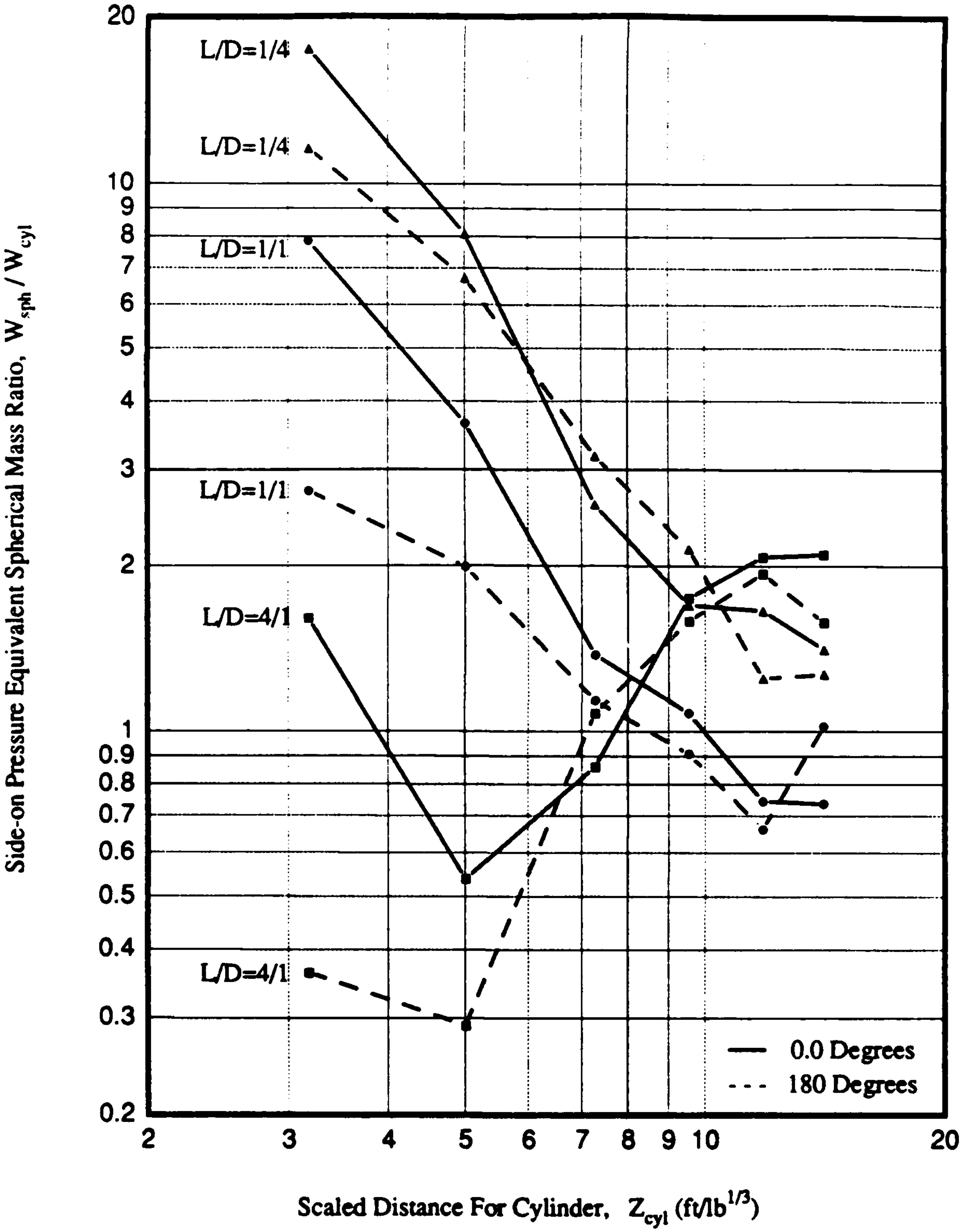

Figure 4. Equivalent Spherical Mass Ratio Bsed on Experimental Side-on Pressures at 0° and 180° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

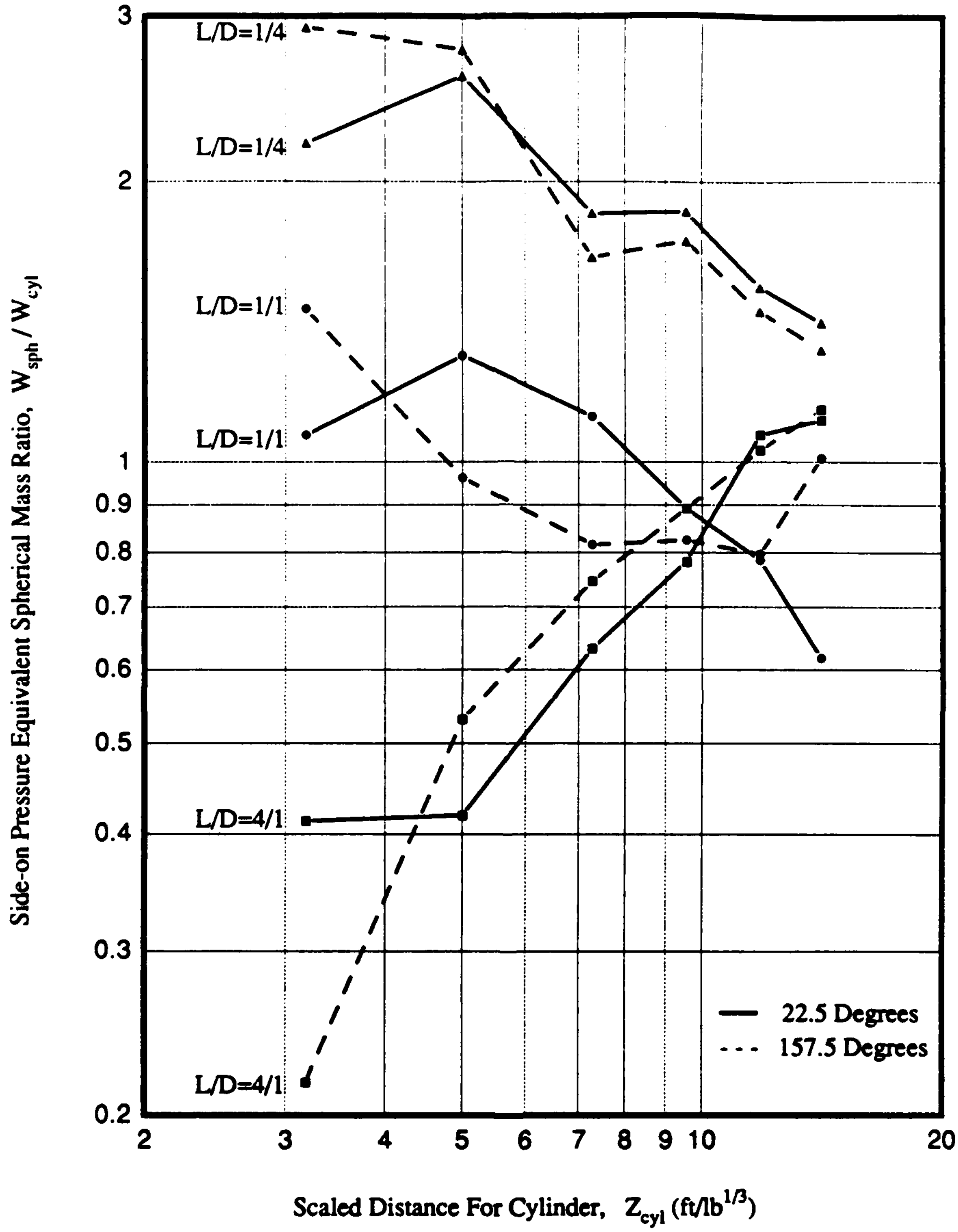

Figure 5. Equivalent Spherical Mass Ratio Based on Experimental Side-on Pressures at 22.5° and 157.5° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

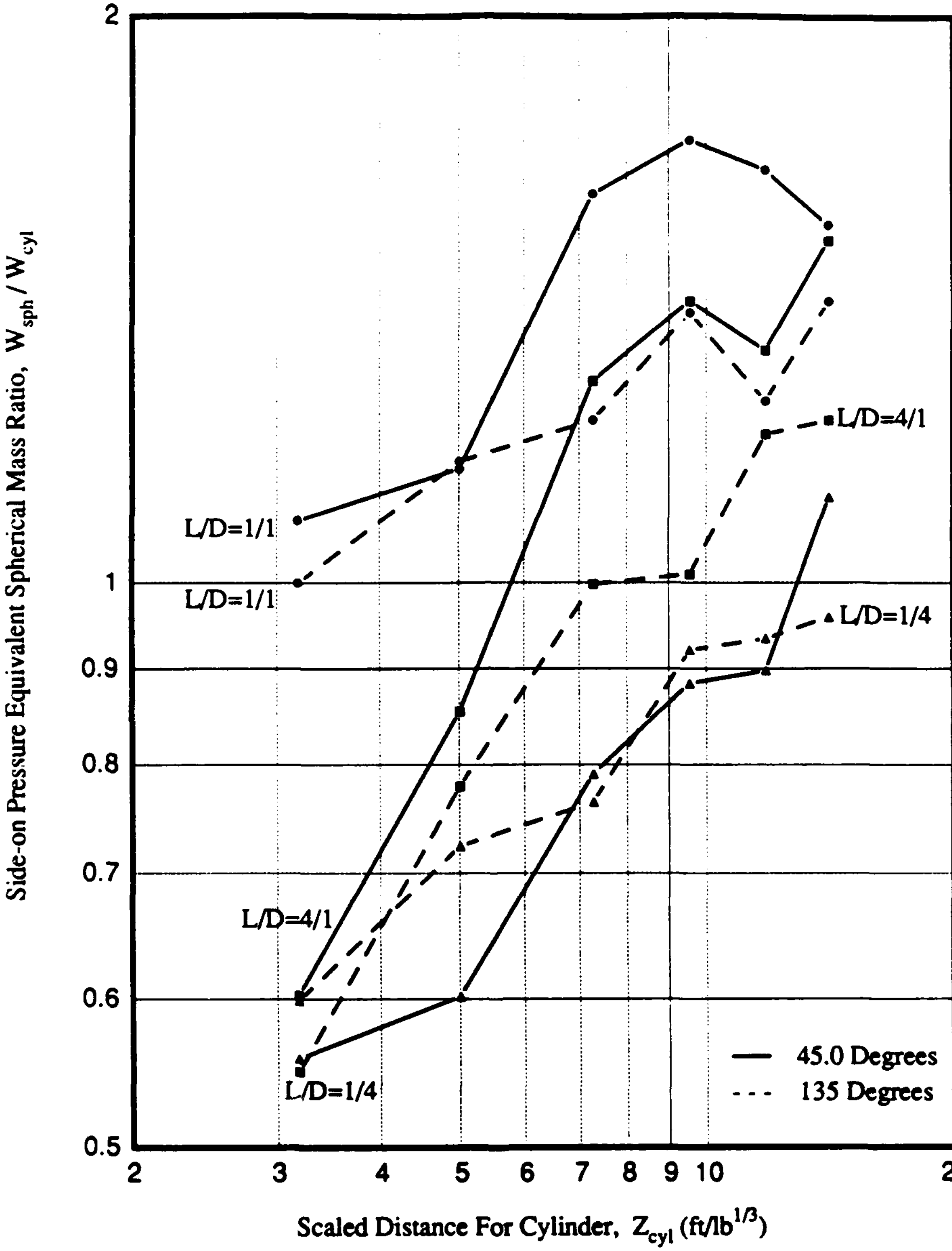

Figure 6. Equivalent Spherical Mass Ratio Based on Experimental Side-on Pressures at 45° and 135° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

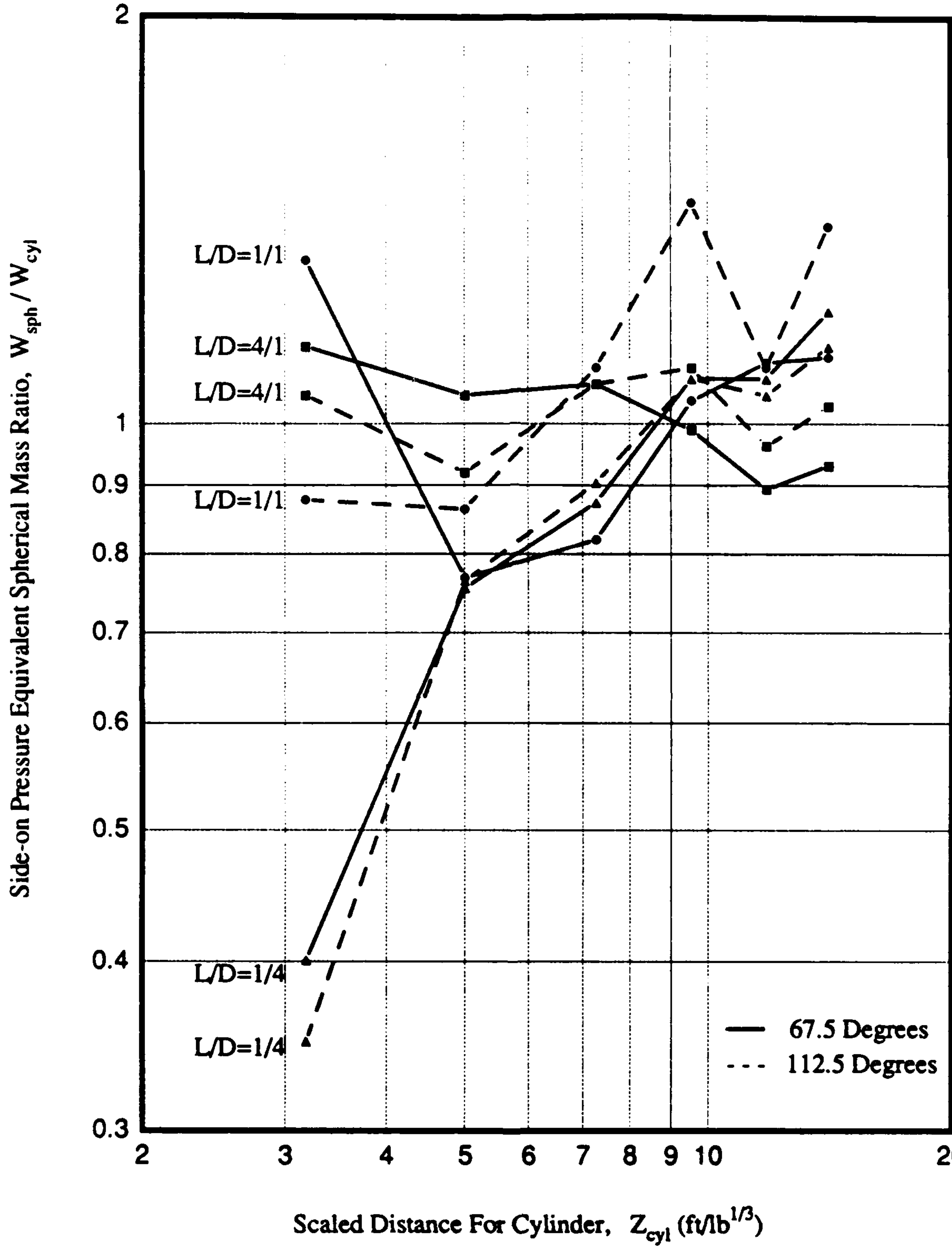

Figure 7. Equivalent Spherical Mass Ratio Based on Experimental Side-on Pressures at 67.5° and 112.5° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

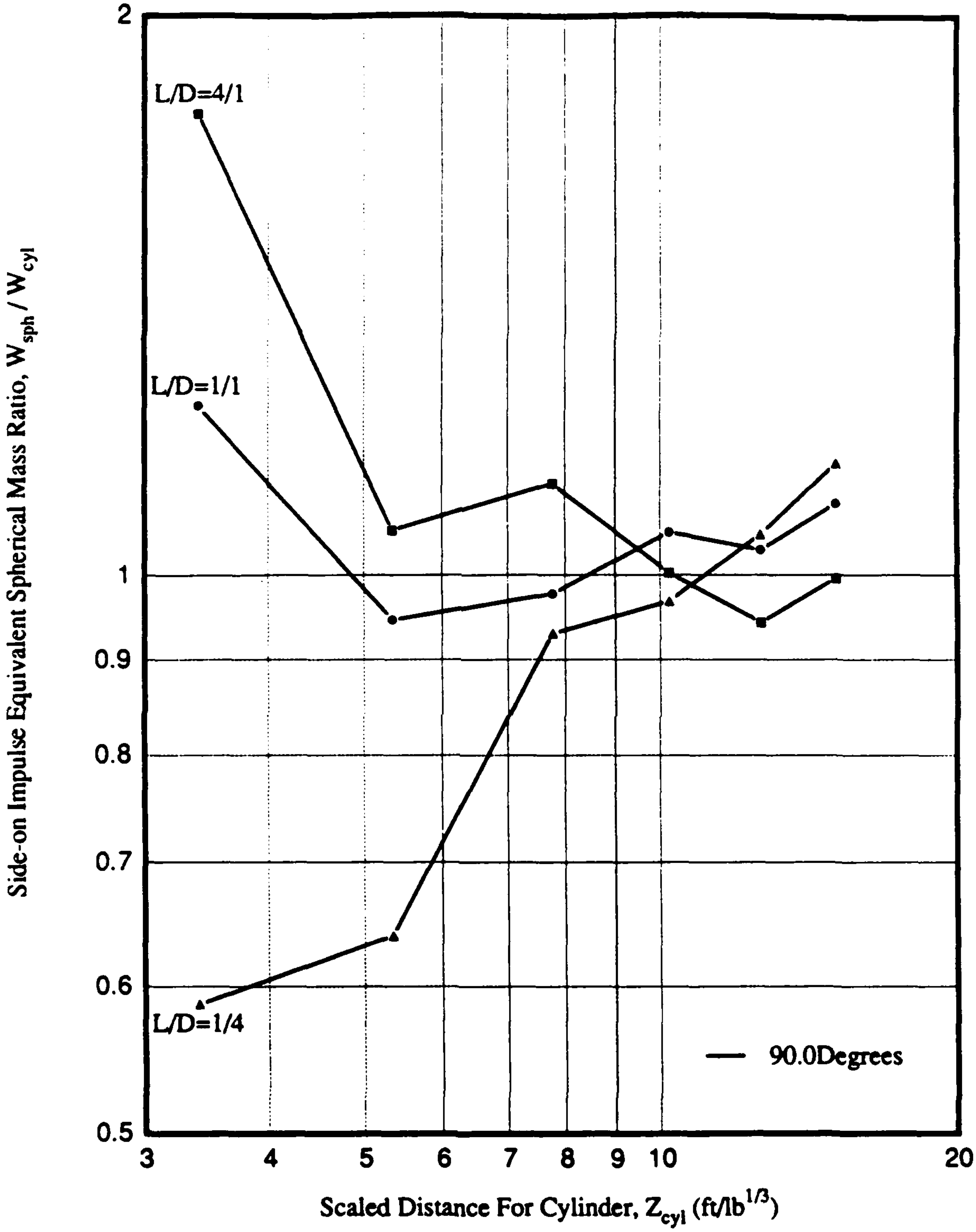

Figure 8. Equivalent Spherical Mass Ratio Based on Experimental Side-on Impulse at an Azimuth Angle of 90° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

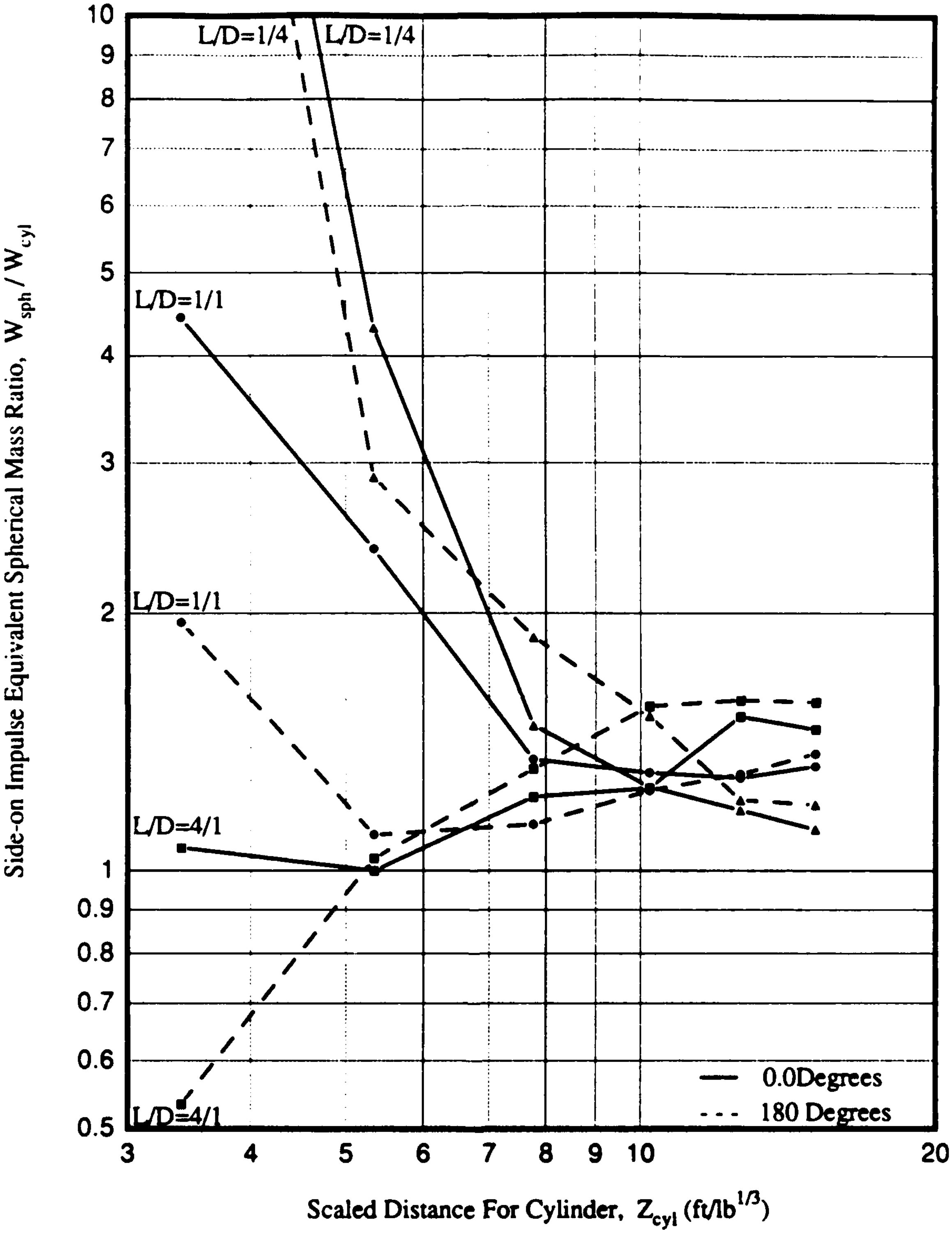

Figure 9. Equivalent Spherical Mass Ratio Based on Experimental Side-on Impulse at 0° and 180° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

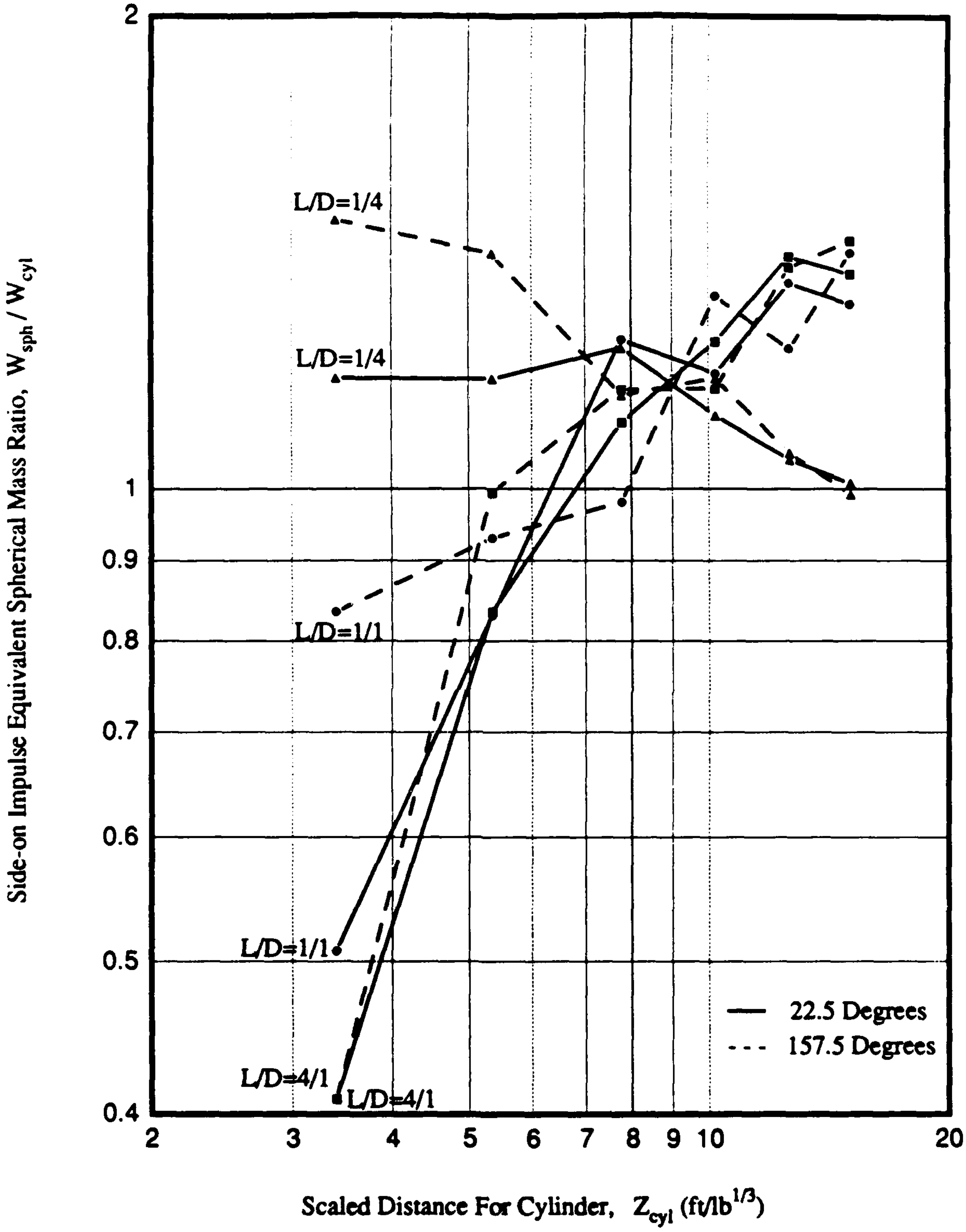

Figure 10. Equivalent Spherical Mass Ratio Based on Experimental Side-on Impulse at 22.5° and 157.5° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

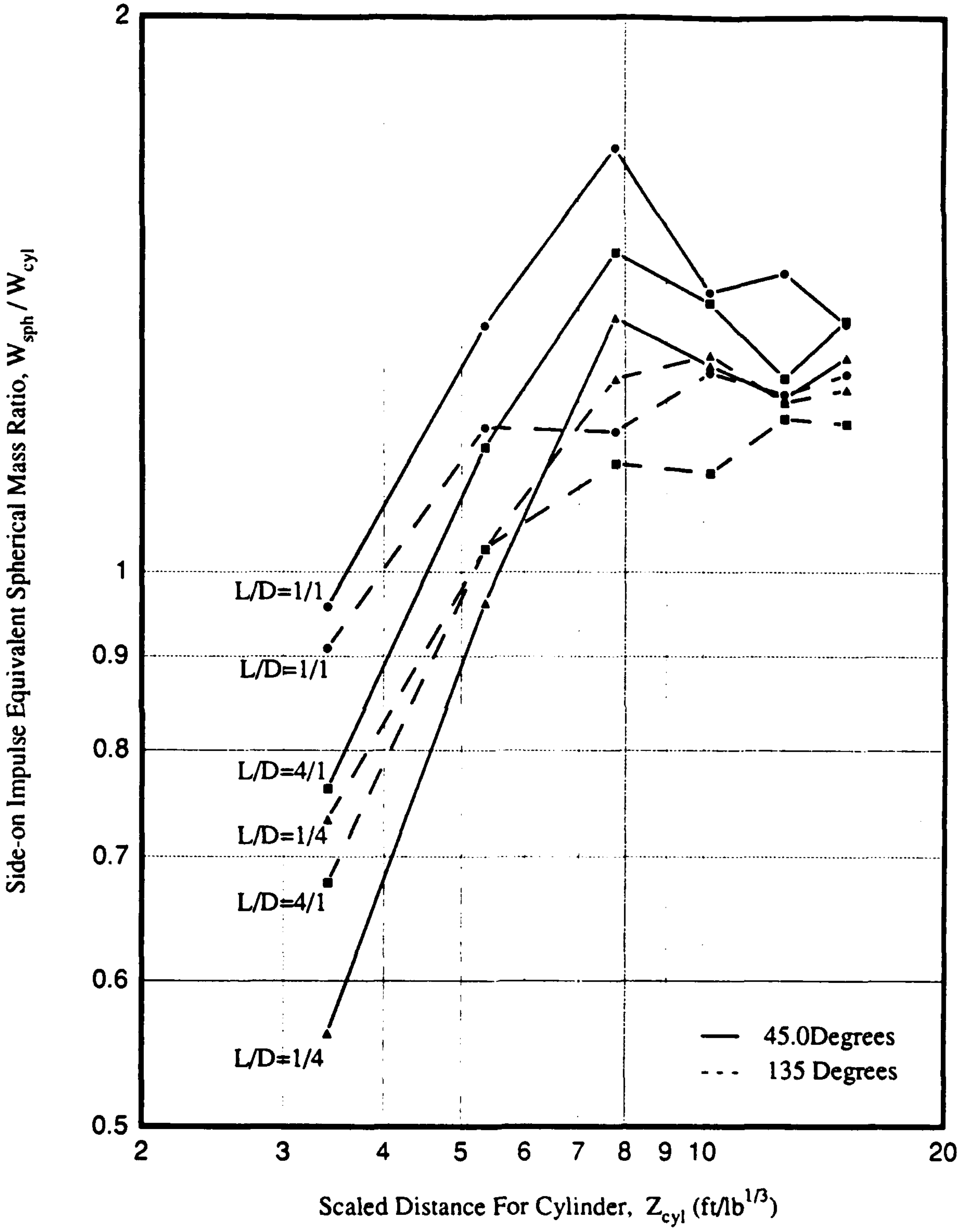

Figure 11. Equivalent Spherical Mass Ratio Based on Experimental Side-on Impulse at 45° and 135° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

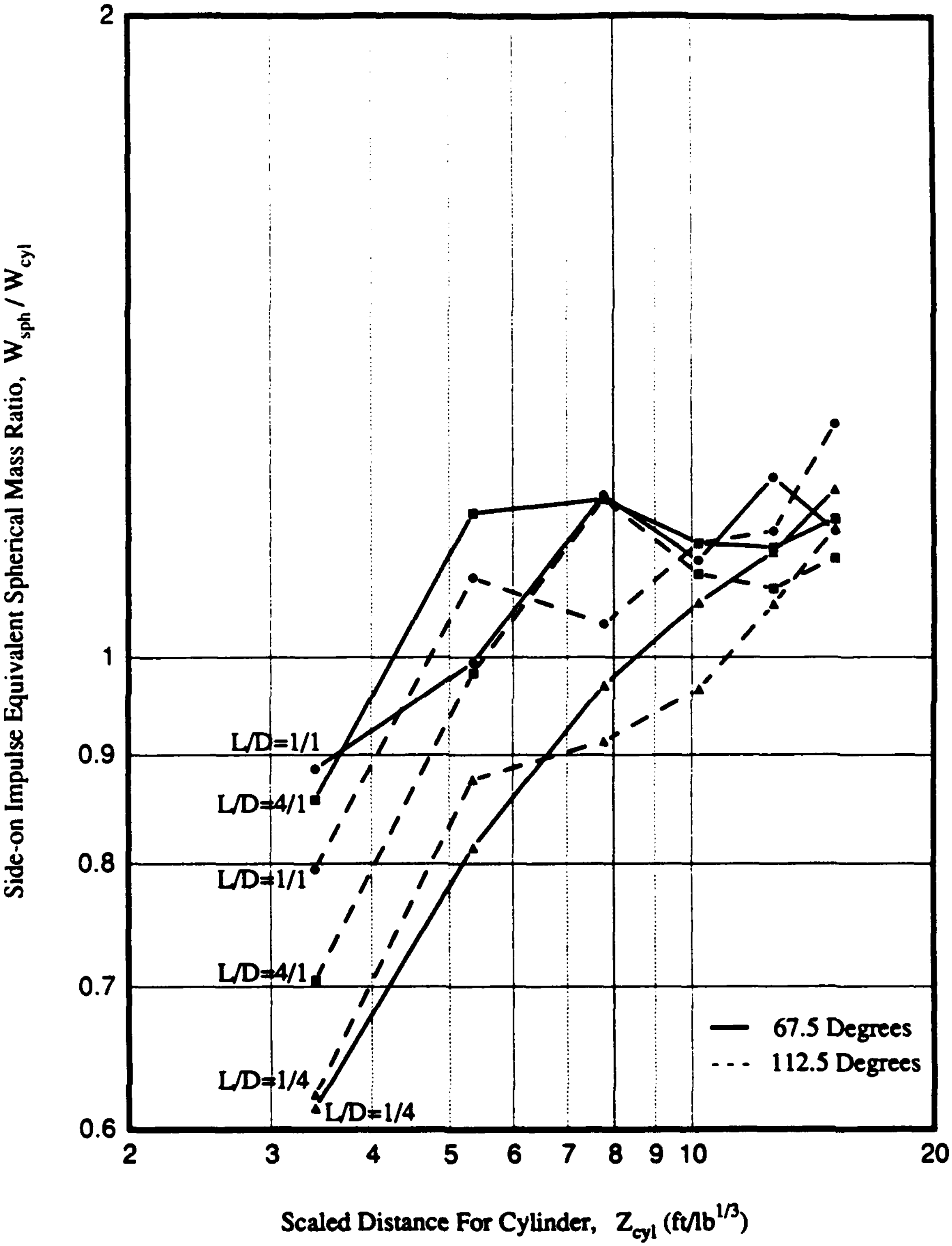

Figure 12. Equivalent Spherical Mass Ratio Based on Experimental Side-on Impulse at 67.5° and 112.5° for a Cylindrical TNT Charge Detonated in Free-Air at Sea Level

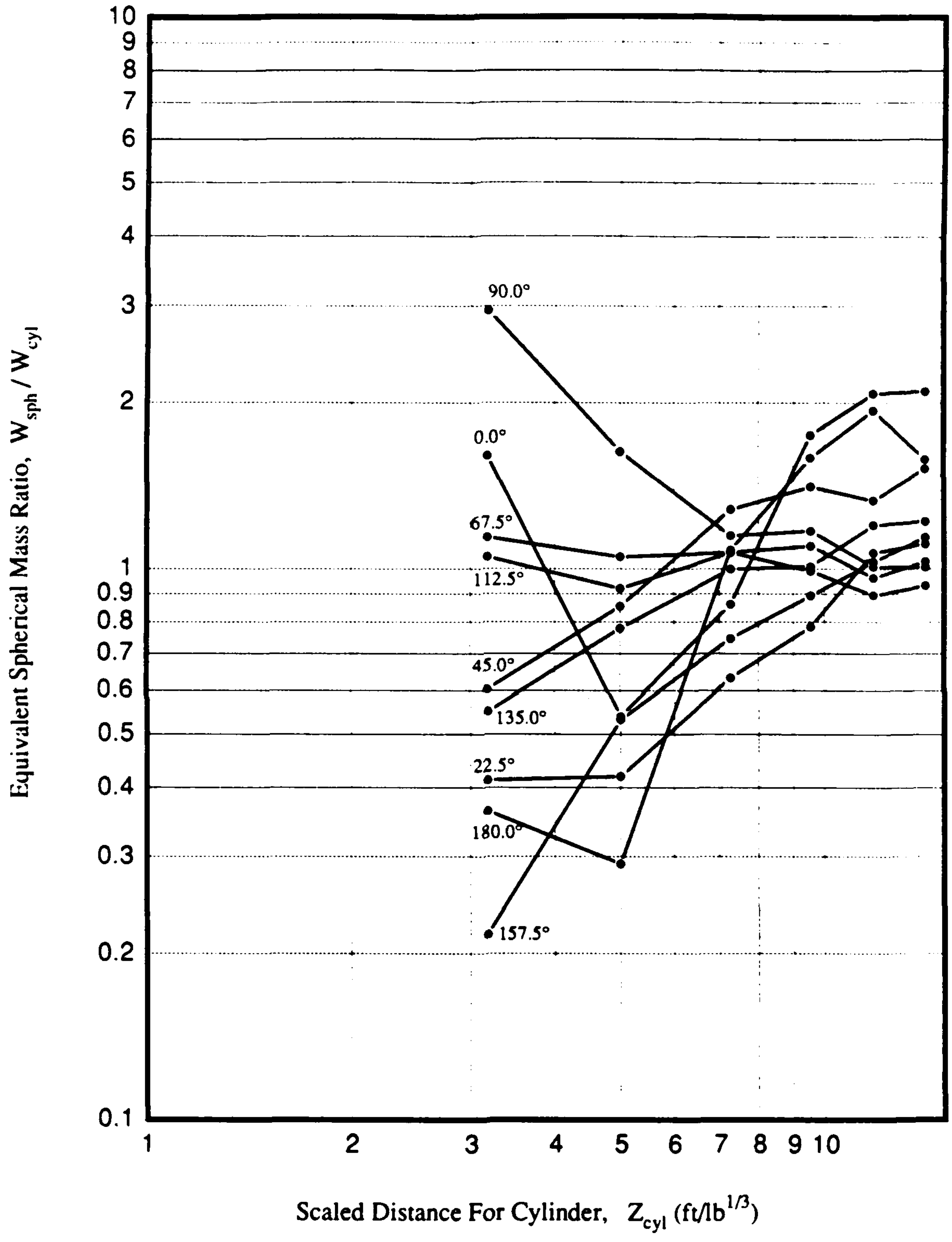

Figure 13. Equivalent Spherical Mass Ratio Based on Side-on Pressure for a Free-Air TNT Cylindrical Charge of L/D = 4/1

W_{cyl} (lb TNT)	R (ft)	$\frac{R}{W_{cyl}^{1/3}}$	θ	$\frac{W_{sph}}{W_{cyl}}$	W_{sph} (lb TNT)	$\frac{R}{W_{sph}^{1/3}}$	P_s (psi)
57.4	25	6.48	0°	1.8	103.3	5.33	25.0
			45°	1.5	86.1	5.66	21.9
			90°	0.86	49.4	6.81	14.7

A spherical charge of the same explosive weight of 57.4 lb at the same standoff distance R of 25 ft would produce a side-on pressure P_s of 16.3 psi. Thus, the difference in the blast pressures produced by the cylindrical charge at that distance can also be presented as ratios of the side-on pressure from the cylindrical charge $P_{s_{cyl}}$ to that from the spherical charge $P_{s_{sph}}$. Therefore, for the above example, the pressure amplitude ratios are:

W_{cyl} (lb TNT)	R (ft)	$\frac{R}{W_{cyl}^{1/3}}$	θ	$P_{s_{cyl}}$ (psi)	$P_{s_{sph}}$ (psi)	$\frac{P_{s_{cyl}}}{P_{s_{sph}}}$
57.4	25	6.48	0°	25.0	16.3	1.53
			45°	21.9	16.3	1.34
			90°	14.7	16.3	0.90

Similar amplitude ratios can be computed using the equivalent spherical mass ratios based on impulse. Note that, in general, the pressure amplitude ratios are quantitatively different from the corresponding spherical mass ratios.

To demonstrate how a cylindrical geometry affects blast loads, amplitude factors as shown above were determined for a cylinder with an L/D = 4/1. A hypothetical problem was devised so that only data from azimuth angles of 22.5° to 90° would be required. Using only the impulse data for the six scaled distances at which measurements were made, amplitude ratios were derived for each of the six scaled distances and smooth curves fitted to extrapolate the data to smaller scaled distances and to interpolate between scaled distances. The results are presented in Figure 14.

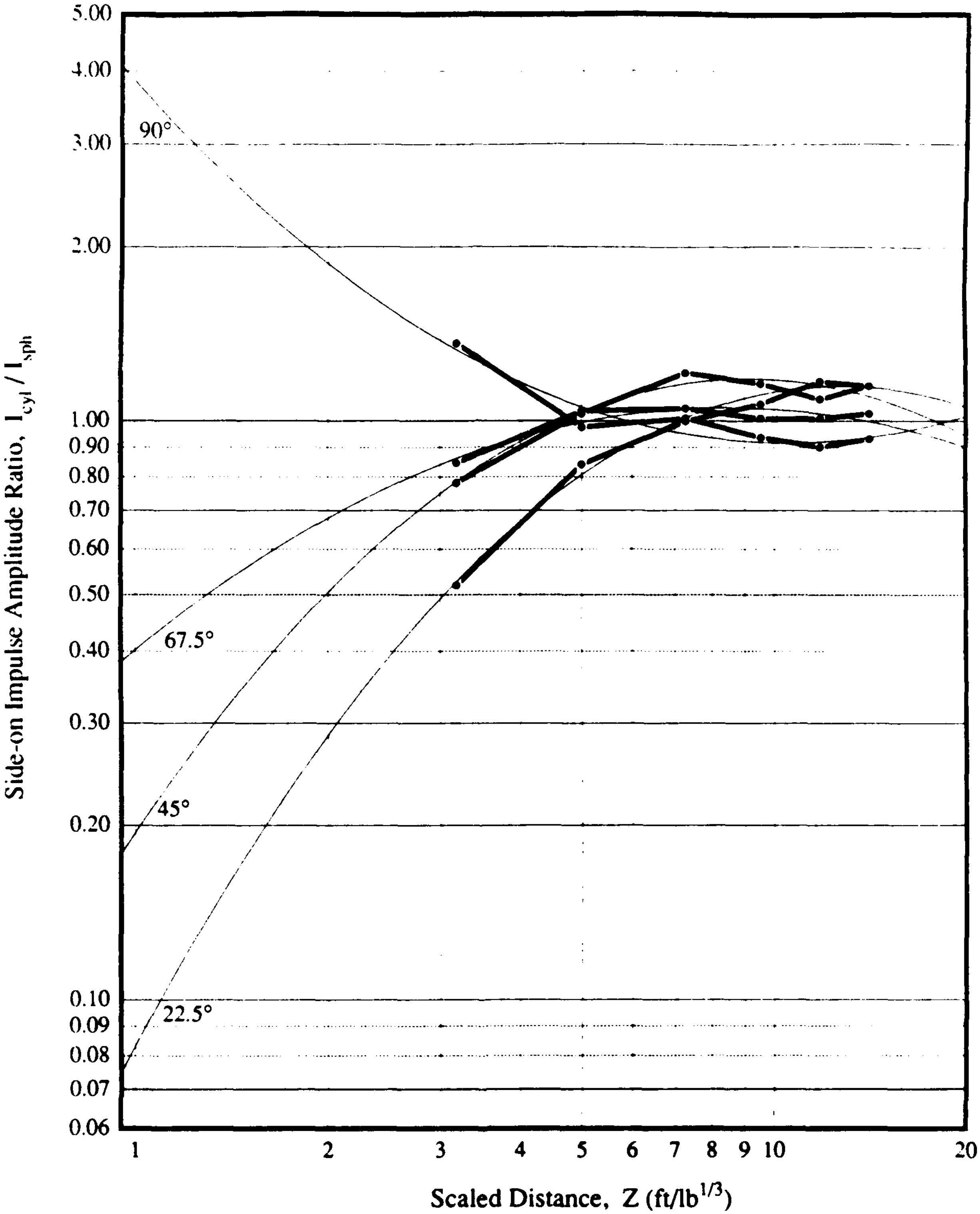

Figure 14. Impulse Amplitude Ratios for a Cylindrical Charge of L/D = 4/1 as Compared to a Spherical Charge

Assuming that reflected impulse will have the same amplitude ratios as side-on impulse, the results presented in Figure 14 were used to estimate the impulsive loads on a flat surface from a free-air cylindrical charge as illustrated in Figure 15. Note that the standoff distance R of 20 ft and the charge weight W of 300 lb were selected such that the cylindrical charge was at a perpendicular scaled distance of 3 ft/lb$^{1/3}$. Thus, very little extrapolation was necessary in using the curves presented in Figure 14. The loads on the flat surface from a spherical charge were first estimated using the computer code CONWEP[21] which has its own set of assumptions. Since the problem is symmetric in two axes, only one quarter of the surface (25 x 15 ft) was used to make the calculations and plot impulse contours as shown in Figure 16. For this case, the average impulse on the quadrant as computed by CONWEP is 210 psi-ms. As expected, the impulse contours are concentric circles. The impulse at the center of each grid element was then adjusted using the curves from Figure 14 for its corresponding azimuth angle and scaled distance. The amplitude ratio curves were interpolated linearly for in between azimuth angles. An impulse contour plot for the cylindrical charge is shown in Figure 17. The contours in this figure are no longer concentric circles and depict quite vividly the effect of the cylindrical charge geometry on the impulse distribution. The average impulse on the quadrant from the cylindrical charge is 325 psi-ms. In a recent limited study by SwRI reported in Reference 22, a similar analysis was used to estimate reflected pressures and impulses on a vertical wall from the detonation of a vertical bomb at the ground surface. In that study, extrapolation of the test data was necessary to a scaled distance of 1.24 ft/1b$^{1/3}$.

CLOSURE

Experimental side-on pressure and impulse data found in the literature from cylindrical charges in free-air were analyzed and used to develop spherical equivalency factors for nine azimuth angles ranging from 0 to 180°. The cylindrical charges of length-to-diameter ratios of 1/4, 1/1, and 4/1 were initiated at the 180° end and measurements made along radial increments of 22.5°. The spherical equivalency factors show the significant difference a cylindrical geometry has on the side-on pressure and impulse, particularly at the smaller scaled distances. These equivalency factors are based on data found in the literature that were measured at scaled distances of about 3 to 15 ft/lb$^{1/3}$. Consequently, the application of this analysis should be limited to scaled distances in this range.

To demonstrate the effect a cylindrical geometry has on blast loads, amplitude factors based on the impulse measurements were computed, extrapolated slightly, and applied in a hypothetical problem to the reflected impulsive loads on a flat surface. In this application it was assumed that

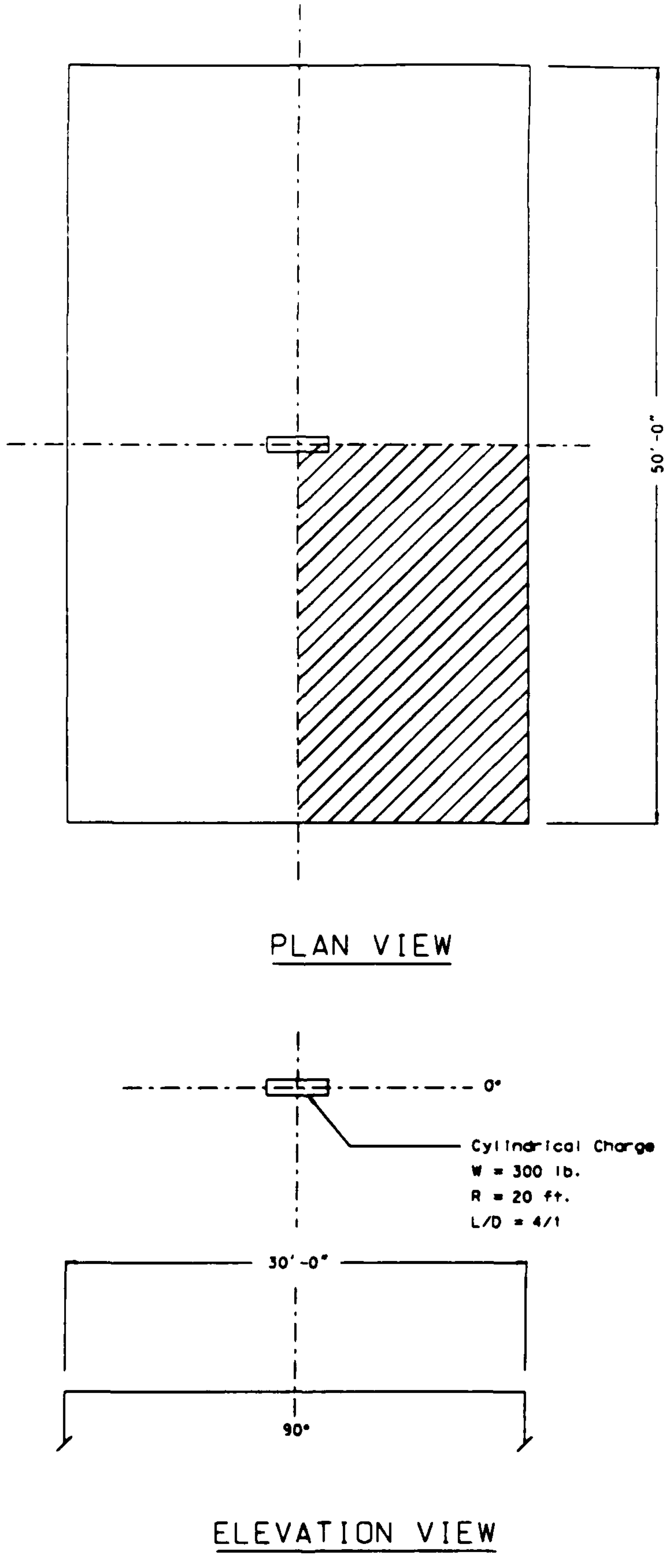

Figure 15. Free-Air Cylindrical Charge Loading a Flat Surface

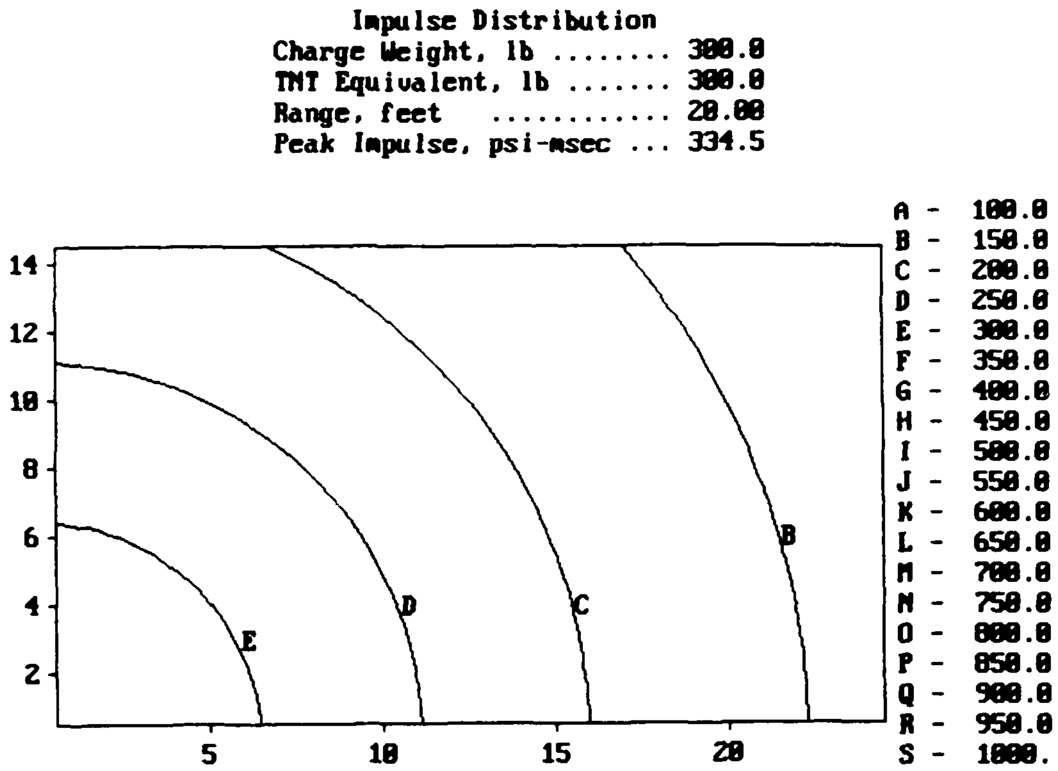

Figure 16. Impulse Contours for a Spherical Charge

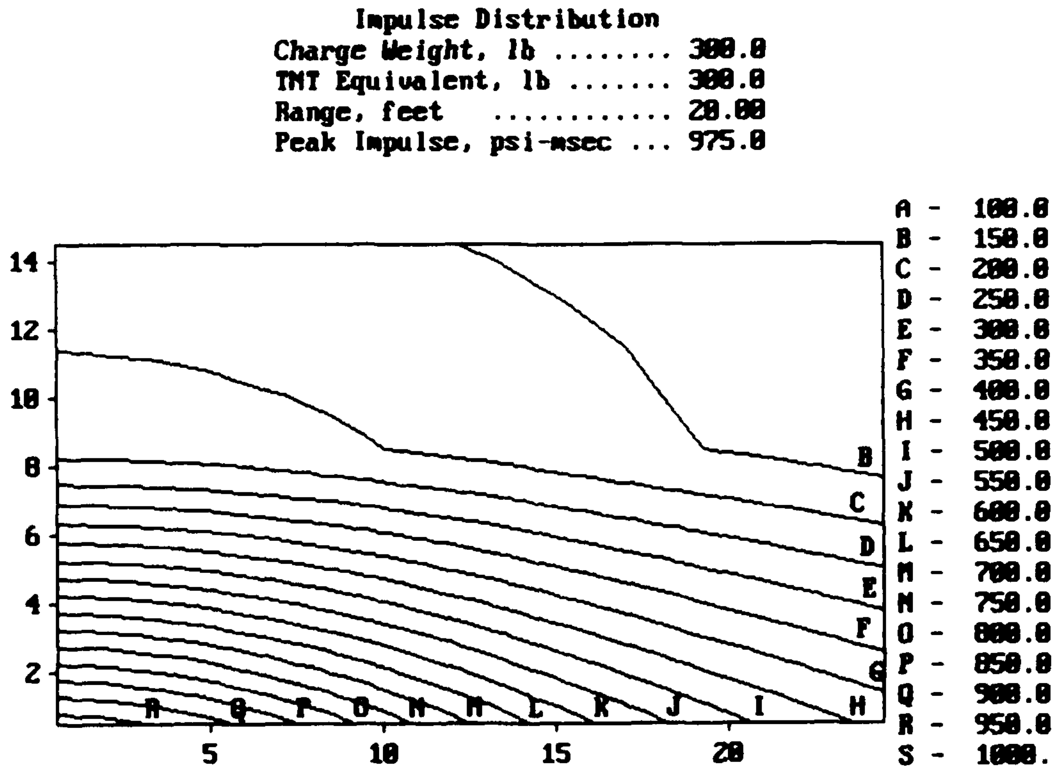

Figure 17. Impulse Contours for a Cylindrical Charge of L/D = 4/1

reflected impulse would have the same amplification factors as side-on impulse. The resulting contour plots depicted quite well the significant difference a cylindrical charge makes on the impulsive loads as compared to a spherical charge.

Considerably more experimental research and data analysis are needed to characterize air blast loads from cylindrical and other nonspherical explosive charges. In particular, measurements of normally and obliquely reflected pressure and impulse are almost nonexistent at small scaled distances where the effects of geometry are most significant. Data are lacking not only from free-air charges, but also from charges on the ground surface. It would be very interesting to determine how close to reality the amplification factors for the illustrated problem really are. The spherical mass ratios presented in this paper provide a means for estimating loads from cylindrical charges of three aspect ratios at scaled distances of about 3 to 15 $ft/lb^{1/3}$. Additional data closer to the charge and with cylinders of other aspect ratios would increase the confidence of the curves presented here.

ACKNOWLEDGEMENTS

Most of the analysis and development of spherical equivalency factors presented in this paper were accomplished as part of the project to revise the U.S. Department of Energy DOE/TIC Manual 11268. Mr. Steve Young of Battelle Pantex was the DOE technical representative and Ms. Patricia Bowles was the SwRI project manager. The author appreciates the resources provided by SwRI to do the additional analysis on amplification factors, and to prepare and present this paper. In particular, the author thanks Mr. Wendell Bielefeld for his significant contribution in the data analysis and curve fits, and for processing most of the figures in this paper. Mr. Jeff Peterson prepared some of the illustrations and Ms. Terry Sloan processed the manuscript.

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AIR-BLAST CHARACTERISTICS OF

AN ALUMINIZED EXPLOSIVE

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ABSTRACT

Air-blast characteristics of an aluminized explosive (RDX/ammonium perchlorate/aluminum/binder 20/43/25/12) were investigated . The TNT-equivalent weight factor of this explosive was experimentally determined as a function of peak pressure in the pressure range of from 0.7 to 120 psi. This factor was 0.9 for pressures over 10 psi (incident-wave region) and increased to 1.2 for pressures lower than 10 psi (Mach-wave region). It is believed that this increase in the TNT-equivalent weight factor in the low pressure region should be attributed to slow energy release from oxidation reaction of aluminum powder added in the explosive.

I. INTRODUCTION

When an explosive charge explodes in air, a shock wave is generated by the rapid release of chemical energy and it propagates through air. Properties of the blast wave represent some aspects of performance of an explosive charge, especially total energy release within relatively long time, compared to reaction time in military explosives. Therefore measuring blast parameters such as pressure and impulse makes it possible to deduce performance related with energy release; total energy release and approximate release rate.

The scaling law was developed to predict blast parameters for charges of an arbitrary weight. According to the scaling law, blast parameters are functions of only a scaled distance. The scaled distance is given by a distance from the explosion center divided by the cube root of charge weight [1]: $Z = R/W^{1/3}$, where Z is the scaled distance, R the distance, and W the charge weight. Since the total energy is determined directly by charge weight of a given explosive, it can be easily deduced that the scaling law is based on the assumption that blast parameters are related with the total energy release.

Different explosives release different amount of energy. The concept of TNT-equivalent weight factor (TNT EWF) was introduced to incorporate the difference in energy release between different explosives into the scaling law. The TNT EWF is defined as the ratio of the weight of a test explosive to the weight of a TNT charge which produces the same blast effect at the same distance. For most single-molecular explosives or mixtures of those explosives, energy release occurs within a very short time (in the order of 0.1 μs) compared to the time scale in which blast parameters are measured (in the order of 1 ms) so that the small difference in energy-release rate can be neglected. For this reason, the scaling law works well for most explosives. For these explosives, the TNT EWF is determined by using experimental data in a relatively high pressure range,

typically over 5 psi. Although this factor is not constant, the deviation is not so big that the average value determined over the tested range of pressure is used in most applications.

It has been experimentally known that blast effect of an explosive can be enhanced by adding slow-burning energetic materials such as fine aluminum powder into the explosive. In this case, only a fraction of energy is released before the sonic point. As a result, the detonation velocity and pressure of this type of explosives are much lower than those of single-molecular explosives. Therefore it is natural to expect that the TNT EWF of this type of explosives be relatively low compared to those of single-molecular explosives for small scaled distance and that it increase gradually with increasing scaled distance. For this reason, using the TNT EWF determined in relatively high pressure region may result in errors in some applications.

The objective of this study is to experimentally evaluate the air-blast characteristics of an aluminized explosive in a wide range of pressure.

The plan of this paper is the following. Section 2 introduces the scaling law and the concept of the TNT-equivalent weight factor. Section 3 describes experimental techniques. Section 4 discusses the experimental results. Section 5 concludes this paper.

II. THE SCALING LAW

The scaling law for explosions is based on fundamentals of geometrical similarity: the ratio of volumes of two spheres is proportional to the third power of the ratio of diameters. Since the characteristics of a blast wave generated in an explosion depend mostly on the explosion energy release, two explosive charges of similar geometry and of the same explosive composition, but of different size, can be expected to give identical blast-wave intensities at distances which are proportional to the cube root of the respective energy release, or weight. This law is called Hopkinson's scaling law [2] after the formulator.

In this scaling law, the scaled parameters are [1]:

$$Z = R/W^{1/3} \quad \text{or} \quad R/E^{1/3} \quad \text{scaled distance} \tag{1}$$

$$\tau = t_a/W^{1/3} \quad \text{or} \quad t_a/E^{1/3} \quad \text{scaled time} \tag{2}$$

$$\eta = I/W^{1/3} \quad \text{or} \quad I/E^{1/3} \quad \text{scaled impulse} \tag{3}$$

where R is the distance from the explosion center, W the weight of an explosive charge, E the energy release of the explosion, t_a the arrival time of the blast wave generated by the explosion, and I the impulse. Then, blast-wave parameters, pressure, P, velocity, U, scaled time, τ and impulse, η, are given by unique functions of the scaled distance, Z, as follows:

$$P = P(Z) \tag{4}$$

$$\tau = \tau(Z) \tag{5}$$

$$U = U(Z) \tag{6}$$

$$\eta = \eta(Z) \tag{7}$$

Theoretically, once blast parameters are determined for a reference explosive, blast parameters of different explosives can be obtained from Equations (1) to

(7) if their weight or energy release is known. Usually, tables of blast parameters obtained from explosion of one ton of a reference explosive, usually TNT, are used as a reference (see reference [3]).

The scaling law and relationships expressed in the above equations may also be used in an inverse sense. They, then, permit the determination of the energy release for a given explosion from experimental data such as peak overpressure. The ratio of the energy release of a test explosive charge to that of a reference explosive charge of the same weight is called the equivalent weight factor (EWF). When blast parameters such as peak overpressure for the test explosive charge measured at the distance, R_t, are the same with those for a reference explosive charge at the distance, Z_r. Assuming that the experimental configurations for both charges are the same, the EWF of the test explosive is determined by using Hopkinson's scaling law, as follows:

$$R_r / W_r^{1/3} = R_t / (\mathcal{E}\, W_t)^{1/3} \tag{8}$$

so that

$$\mathcal{E} = (Z_t / Z_r)^3 \tag{9}$$

where

$$Z_t = R_t / W_t^{1/3}$$

and

$$Z_r = R_r / W_r^{1/3}$$

where $\mathcal{E}$ is the EWF of the test explosive with respect to the reference explosive, and subscripts r and t refer to as the reference explosive and the test explosive, respectively. When TNT is used as a reference explosive, $\mathcal{E}$ is called the TNT EWF.

III. EXPERIMENTAL TECHNIQUES

The test explosive used in this study is DXD-03, an experimental castable plastic-bonded explosive. The formulation of DXD-03 is RDX/AP/Al/binder 20/43/25/12 (weight %). The configuration of this explosive is shown in Figure 1. The density of DXD-03 is 1.78 g/cm^3 and the weight of a charge for this configuration is $\sim$ 13 kg. A booster of 90 g composition A-5 was used to initiate the DXD-03 charge. TNT and composition B charges of the same geometry except booster size were also tested for comparison.

The experimental setup for blast-effect tests is shown in Figure 2. As shown in Figure 2, a cylindrical charge was placed at a height of 1.9 m and was initiated from center. Pencil-type blast pressure gauges, PCB 137A11 and 137A12 manufactured by the PCB Piezoelectronics, Depew, NY, were placed at the same height with the charge and at distances from 3 to 60 m from the center of the charge. Signals from the gauges were amplified by the PCB 464A Dual-Mode Charge Amplifiers manufactured by the PCB Electronics, and recorded by the 6810 Waveform Recorder manufactured by the LeCroy Research Systems Corp., Spring Valley, NY, was used.

IV. RESULTS AND DISCUSSIONS

Experimental peak overpressures for DXD-03, composition B, and TNT in incident-wave and Mach-wave regions are shown in Figures 3 to 8. To calculate the TNT EWF for DXD-03, the data set in each region was fitted to a fourth-order polynomial by a least squared-error method, as is:

$$\ln P = \sum_{i=0}^{i=4} a_i (\ln Z)^i \tag{10}$$

where a_i are adjustable constants. Peak overpressure data for composition B and TNT were also fitted to Equation (10). By using fitted equations, scaled distances for DXD-03 and TNT yielding the same overpressure were calculated. The TNT EWF was calculated by using Equation (9). The results are shown in Figure 9. The TNT EWF for composition B was determined by repeating the above procedure, and the results are plotted in Figure 10.

When it impinges on a surface near grazing incidence, a shock wave produces a Mach wave (or Mach stem). A triple point is the point at which three waves, incident, reflected, and Mach waves, meet altogether. The farther the Mach wave propagates, the higher is the triple point. To check whether a gauge at a certain location is affected by the Mach wave or not, it is necessary to determine the locus of the triple point. The height of the triple point is usually given as a function of the height of the center of the explosion and the gauge height (see reference [4]). The calculated minimum distance at which a gauge was affected by a Mach wave was 6.5 to 7 m for DXD-03, TNT, and composition B charges tested in this study. Pressure records showed that the Mach wave started to affect gauges at 7 m from the explosion center. In the above triple-point calculations, all charges were assumed to be spherical. At the position of 7 m (scaled distance: 3 $m/kg^{1/3}$), the explosive yield of a cylindrical charge is greater than that of a spherical charge for the same weight, the calculated

results might have been overestimated (but not shorter than 6 m).

It has been experimentally found that there exists significant differences in blast characteristics between cylindrical and spherical charges for the same weight. When a ratio of length to diameter is over 1, the explosive yield of a cylindrical charge is greater than that of a spherical charge at relatively small scaled distance and decreases with increasing scaled distance. For a cylindrical charge of 2 kg composition B, its explosive yield was equivalent to that of a 3 kg spherical charge at an overpressure of 60 psi and that of a 1.7 kg spherical charge at an overpressure of 5 psi [5]. In this study, the EWF of the cylindrical TNT charge with a length-to-diameter ratio of 1 is shown in Figure 11. In the above calculations, explosion properties of a spherical TNT charge was obtained from standard tables for explosion of 1 ton charges listed in reference [3]. To eliminate the above geometry effect in evaluating the blast effect of DXD-03, explosive yield of cylindrical TNT charges were used as a reference in this study.

As shown in Figure 9, the TNT EWF for DXD-03 was determined to be 0.9 in relatively high pressure region (incident-wave region) and 1.2 in relatively low pressure region (Mach-wave region). This trend was much different from that of TNT EWF for composition B, which was almost constant in both regions. These results suggested that the energy release of DXD-03 charges was lower than that of TNT charges in early stage of detonation and was greatly increased in later stage.

Experimental detonation velocity and pressure data supported this reasoning. The detonation velocity of DXD-03 was determined to be 5.49 to 5.70 km/s at charge diameters of 45 to 127 mm [6,7]. The BKW code predicted the detonation velocity of DXD-03 to be 7.81 km/s. The detonation pressure measured by the high-resistance manganine-gauge method was 14 GPa [8] while that predicted by the BKW code was 27 GPa. The big difference between the experimental data and the BKW predictions suggested that a significant part of energy be released after the sonic point and that DXD-03 be a nonideal explosive.

Since only a fraction of energy was released before the sonic point, the energy yield of this explosive was measured to be low in vicinity of the charge or in relatively high pressure region. As the rest of the energy was released, the TNT EWF was increased. This energy release behavior is quite different from that of most single-molecular explosives, energy release of which occurs within very short time (in the order of one tenth of μs). Because of this fast energy release, TNT EWF for single-molecular explosives obtained in relatively narrow pressure range may be used in most applications without causing big error. The TNT EWF for nonideal explosives such as DXD-03 obtained in relatively high pressure region, however, cannot be applied to relatively low pressure region.

The pressure criterion in determining inhabitated building distance (IBD) regulated in the DOD standards [9] is 0.9 psi. Using the TNT EWF value for nonideal explosives determined in relatively high pressure region in determining IBD may result in underestimation of IBD. In this case only the TNT EWF value obtained in pressure region near the pressure criterion should be used for correct results.

In conclusion, the addition of aluminum powder caused slow energy release and, consequently, improved energy yield at relatively low pressure region.

V. CONCLUSIONS

The air-blast characteristics of DXD-03, an aluminized explosive, were investigated. The TNT EWF for DXD-03 was determined to be 0.9 in relatively high pressure region and 1.2 in relatively low pressure region. It is believed that the increase in the TNT EWF in relatively low pressure region should be attributed to slow reaction of aluminum powder.

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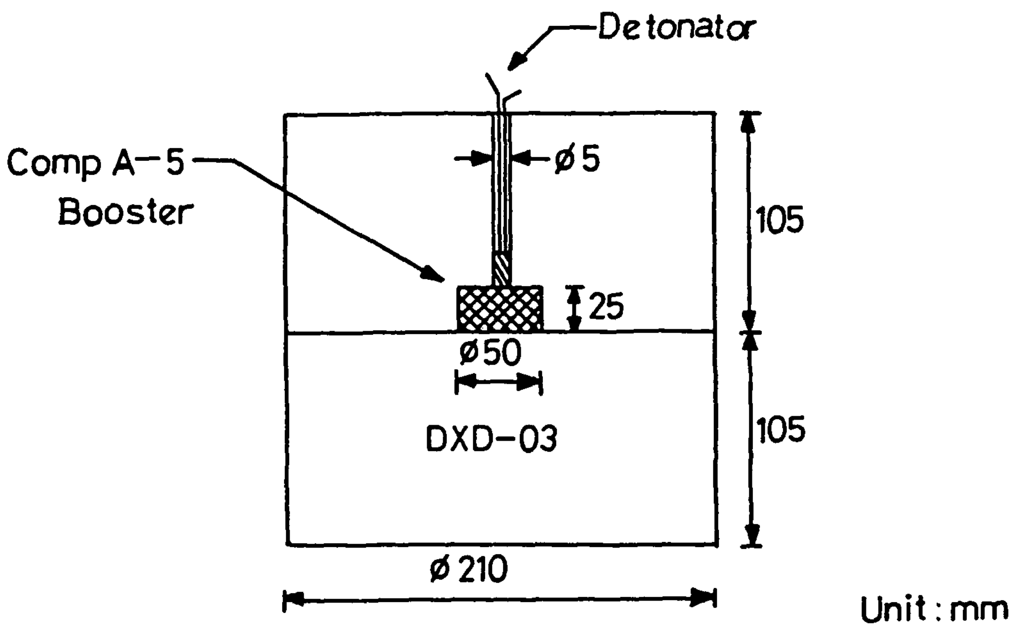

Figure 1. Configuration of a DXD-03 charge (~ 13 kg).

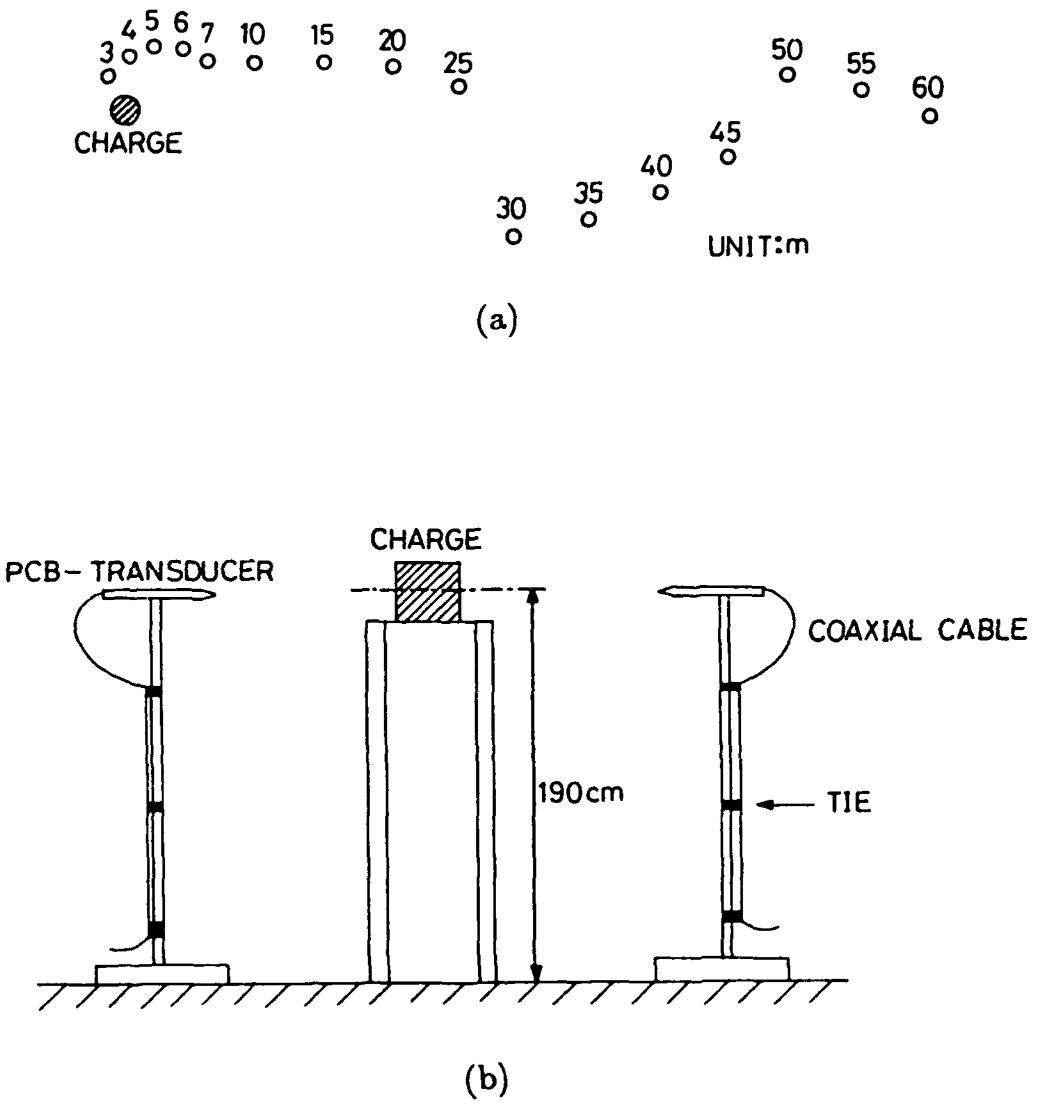

Figure 2. Experimental setup of blast-effect test; (a) gauge location and (b) height of a DXD-03 charge and gauges.

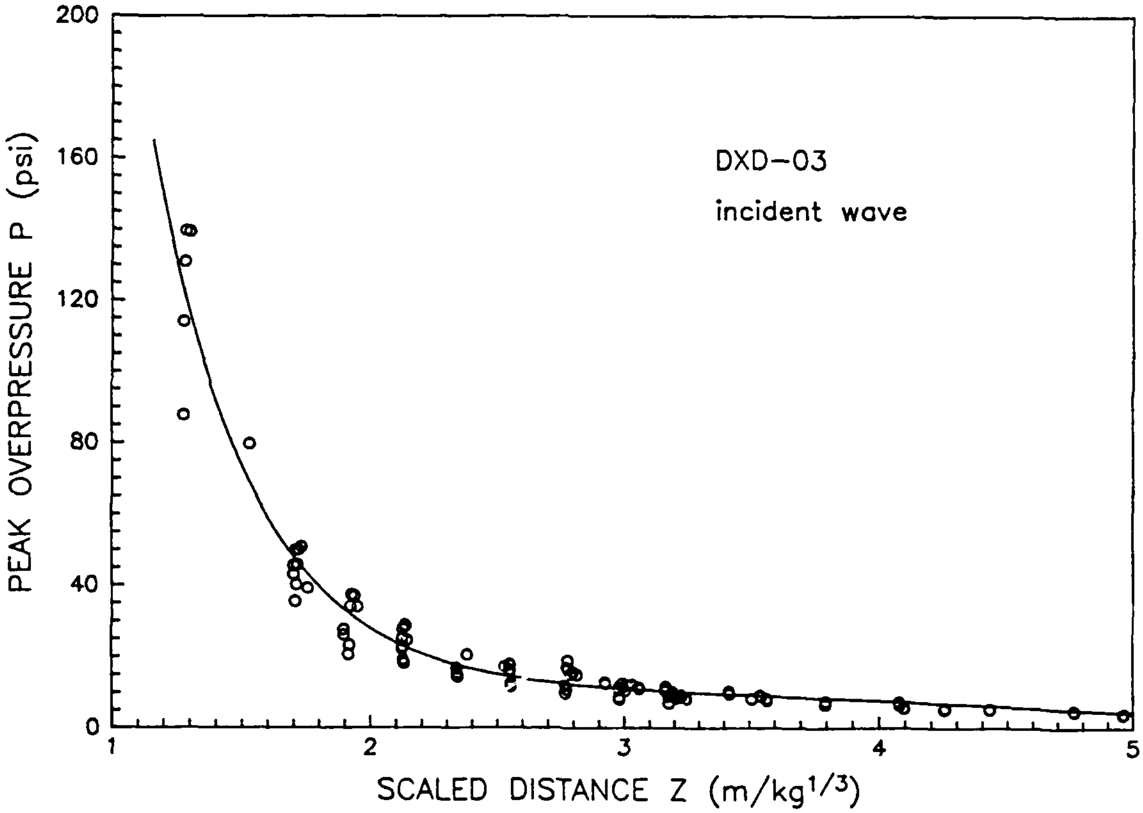

Figure 3. Overpressure as a function of scaled distance in incident-wave region for DXD-03 ($\sim$ 13 kg).

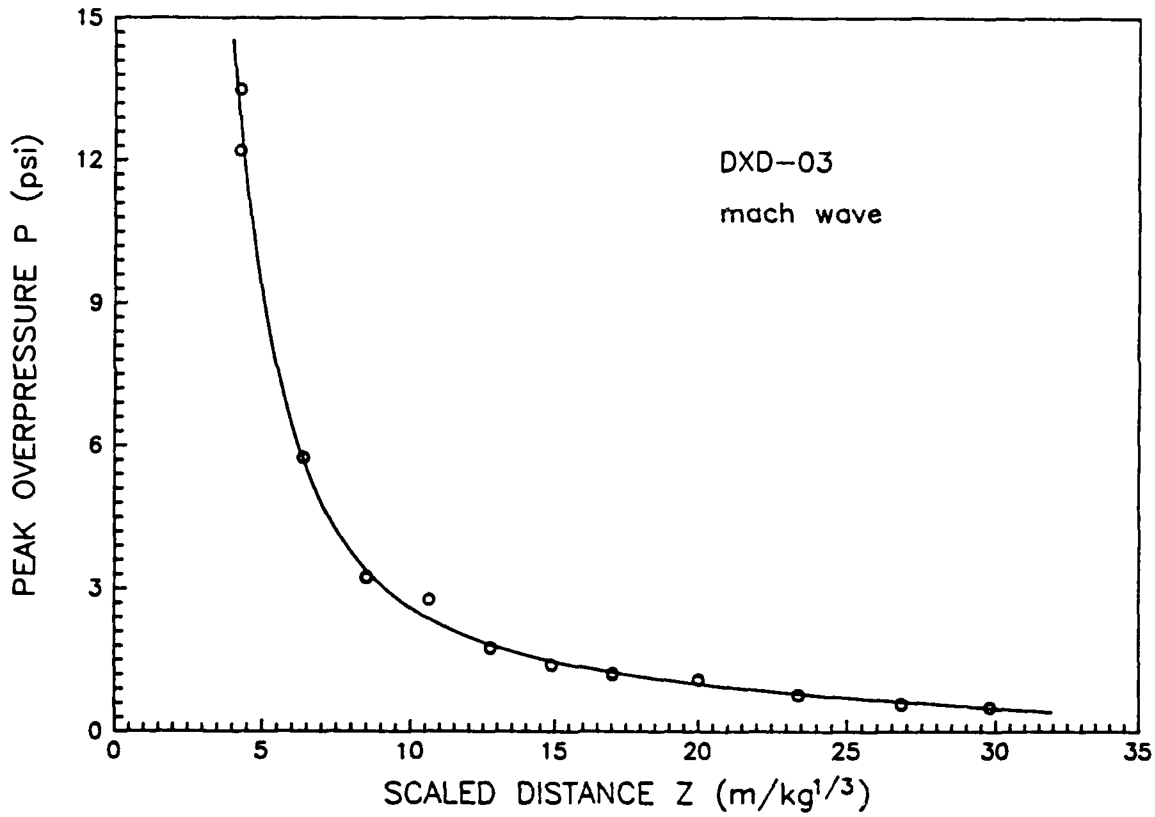

Figure 4. Overpressure as a function of scaled distance in Mach-wave region for DXD-03 ($\sim$ 13 kg).

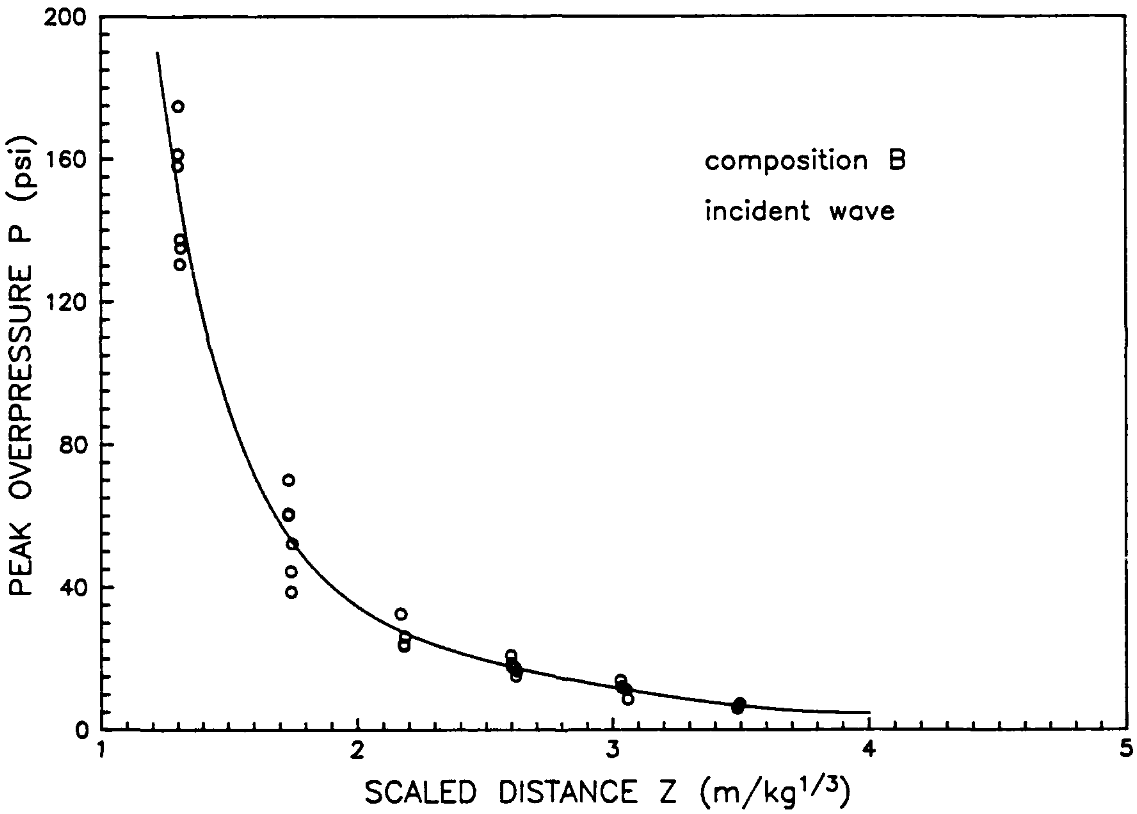

Figure 5. Overpressure as a function of scaled distance in incident-wave region for composition B (~ 12.3 kg).

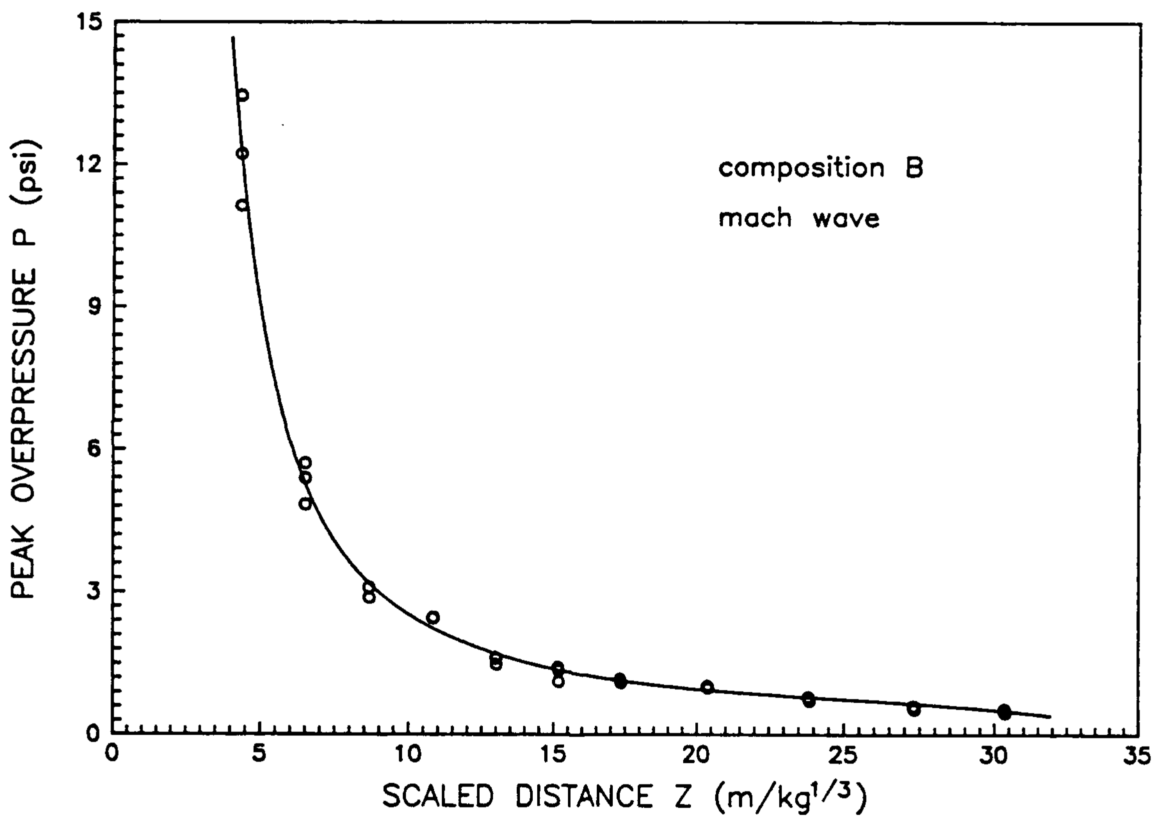

Figure 6. Overpressure as a function of scaled distance in Mach-wave region for composition B ($\sim$ 12.3 kg).

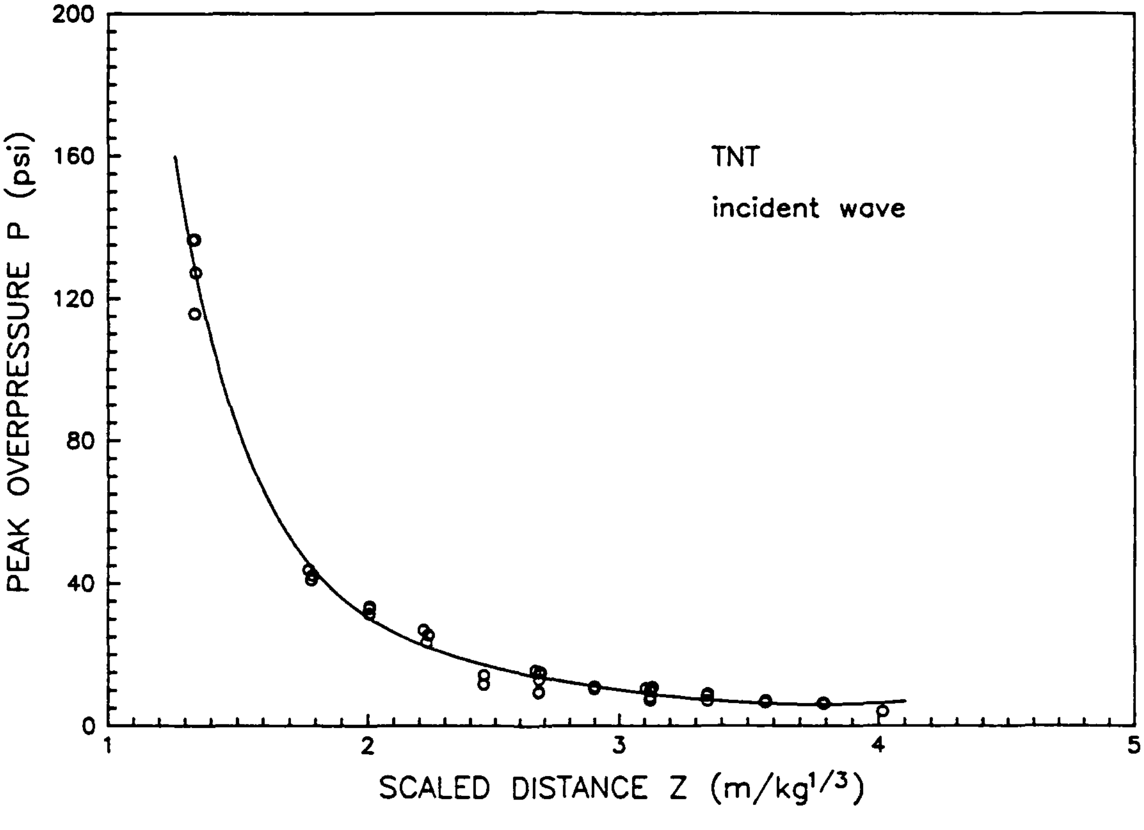

Figure 7. Overpressure as a function of scaled distance in incident-wave region for TNT (~ 11.3 kg).

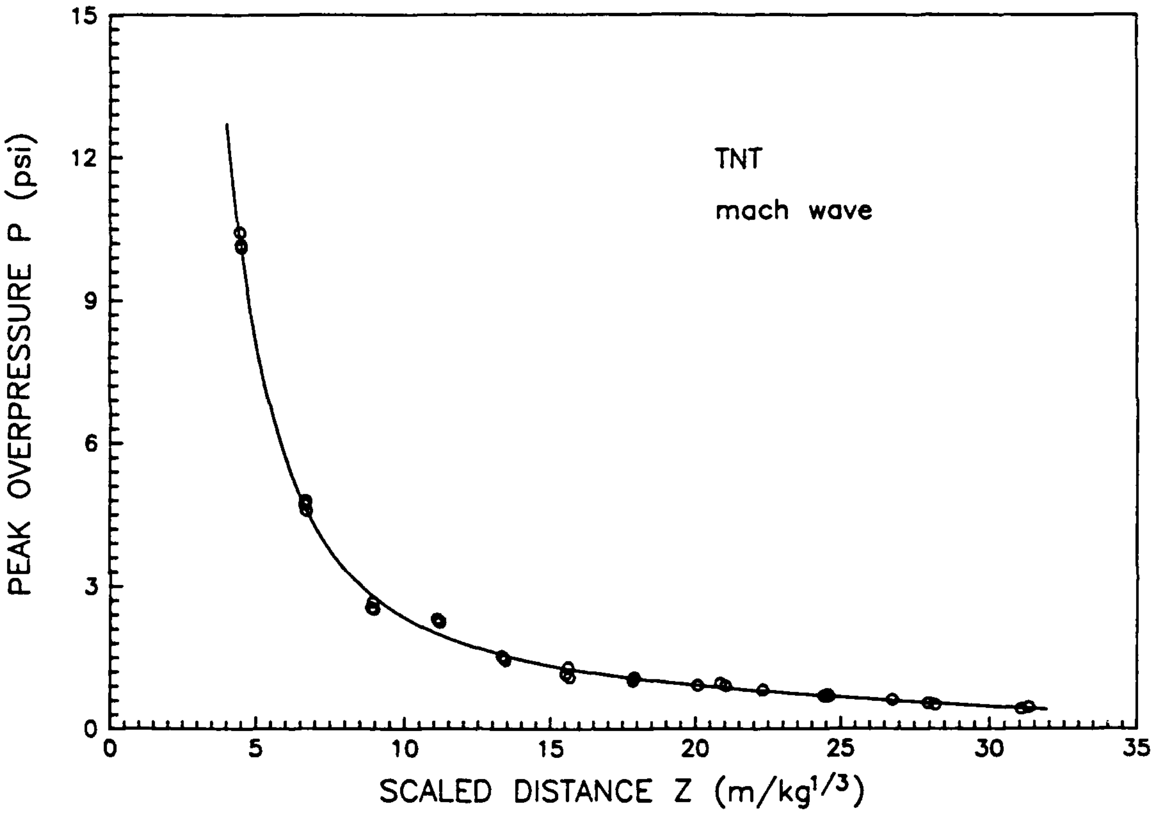

Figure 8. Overpressure as a function of scaled distance in Mach-wave region for TNT ($\sim$ 11.3 kg).

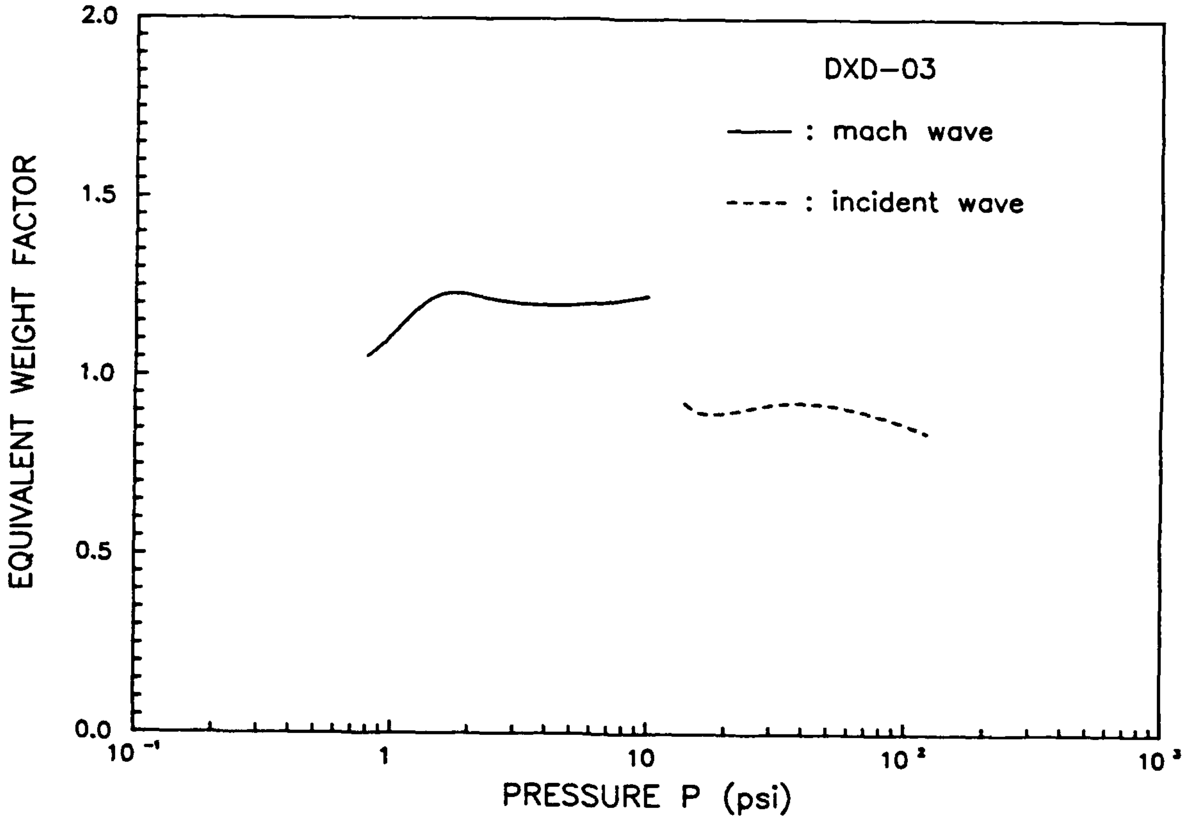

Figure 9. TNT-equivalent weight factor of DXD-03.

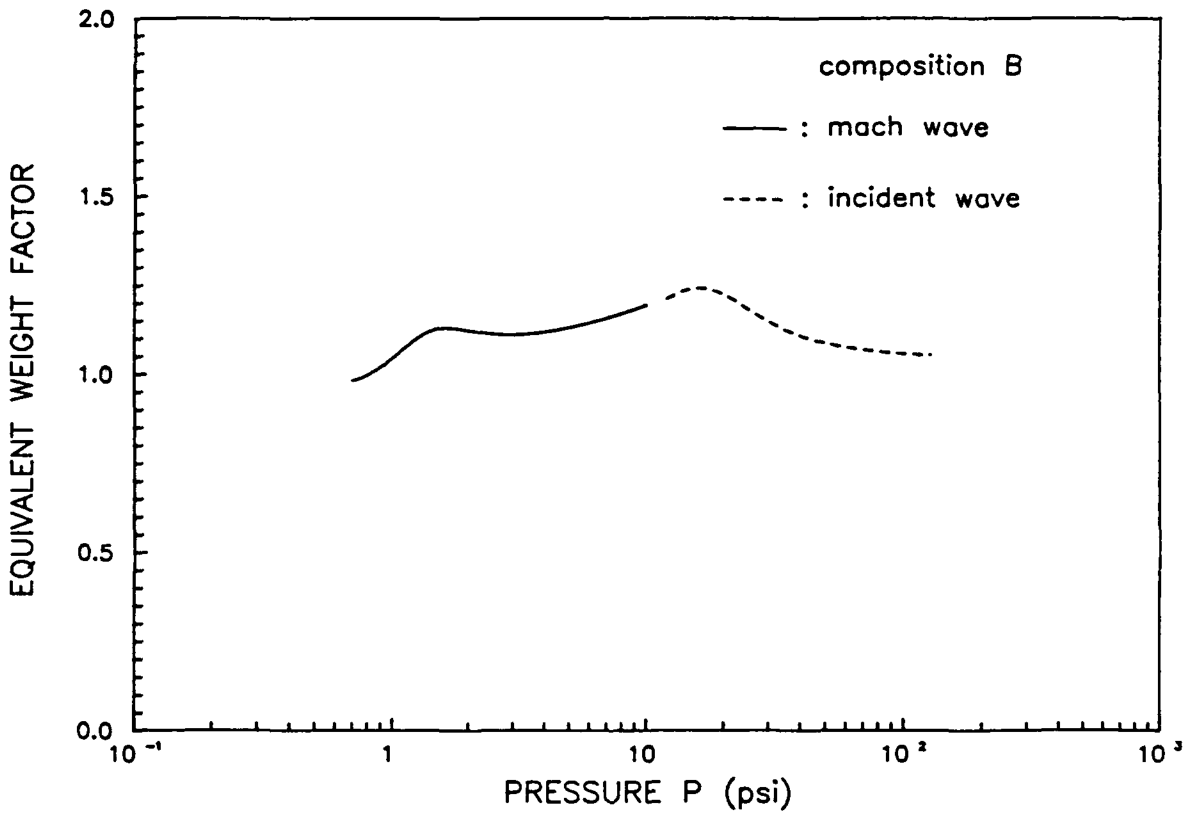

Figure 10. TNT-equivalent weight factor of composition B.

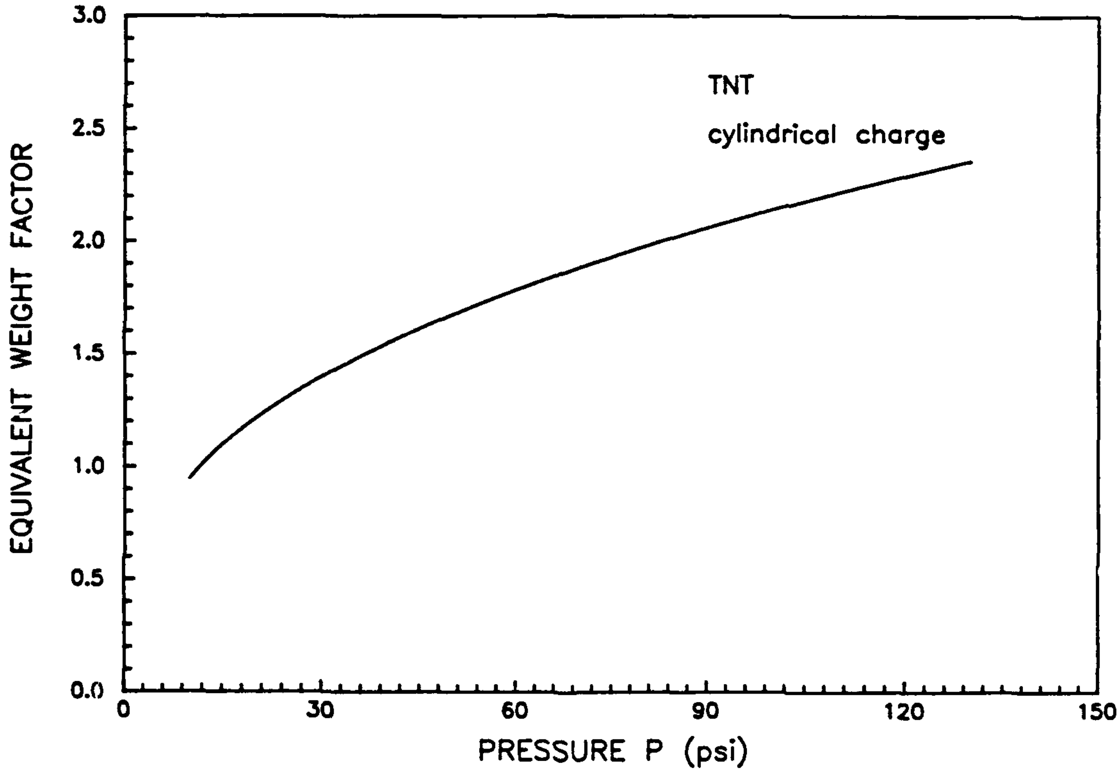

Figure 11. Geometry effect of cylindrical TNT charges (length/diameter = 1) over spherical charges.

Acceptor Loads and Response of an Intervening Sand Wall Barrier from the Simultaneous Detonation of 24 Mk82 Donors[1,2]

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Abstract

Problem. The loads incident on Mk82 acceptors located two feet from the acceptor side of an intervening 3.5 foot sand wall were evaluated with the aid of hydrocodes, literature, and closed form solutions. The donor side of the sand wall was subject to the simultaneous detonation of a 4 by 6 array of 24 Mk82 donors. The leading edge of the donor array was located at a two foot standoff from the sand wall.

Approach. The problem was divided in into three regimes which included: (1) The loads promoted on the sand wall from simultaneous detonation of the donors; (2) The response of the barrier and propagation of the donor loads through the sand wall; and, (3) The interaction of the sand wall barrier with the acceptors.

Results. The extent to which the loads promoted by the donor couple to the intervening sand wall are greatly affected by the stacking configuration of the donors. This is due to the occurrence of jetting which occurs between adjacent rows of donors and the existence of rarefied regions which occurs between adjacent donor columns. The jetting results in local regions of the wall being subject to very intense pressure distributions. The rarefied regions occurring between donor columns last several 100 μsec and thwart propagation of loads toward the wall from adjacent columns of donors.

The sand wall attenuates high frequency components of the incident wave but is relatively ineffective in attenuating the low frequencies which are the major components of the incident wave. The wall becomes rapidly fluidized and the loads incident on the acceptor are to a large extent governed by the fluid-structure interaction between the multi-phase flow from the barrier debris and the stress wave response of the acceptor.

The Naval Civil engineering Laboratory (NCEL) is developing a new High Performance (HP) ordnance magazine. The goal of the magazine is to reduce the land area encumbered by Explosive Safety Distance (ESQD) arcs. This can be accomplished by limiting the Maximum Credible Event (MCE) to detonation of a single cell in the HP Magazine. This cell contains only a portion of the net explosive weight stored in the HP magazine and therefore entails smaller ESQD arcs. A critical component in the design of the HP magazine is a cell wall that prevents Sympathetic Detonation (SD) of explosives stored in adjacent HP magazine cells.

An initial part of the cell wall development effort included the analysis of a 4 by 6 array of Mk82 donors at a two foot standoff from a 3-1/2 foot thick sand wall and a 4 by 3 array of Mk82 acceptors also at a two foot standoff from the sand wall (See Figure 1). The analysis employed closed form solutions, the WONDY hydrocode, and the AUTODYN® 2D finite difference code.

The purpose of this initial phase of the analysis was to describe relevant phenomenology, identify governing parameters, and develop strategies to mitigate the environment at the acceptors.

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1 Presented at the Twenty-Fifth Annual Explosives Safety Seminar at the Anaheim Hilton Hotel in Anaheim, California, 18-20 August 1992.

2 This work was sponsored by the Naval Civil Engineering Laboratory, Contract N47408-90-D-1039, Delivery Orders 4, 9, and 13.

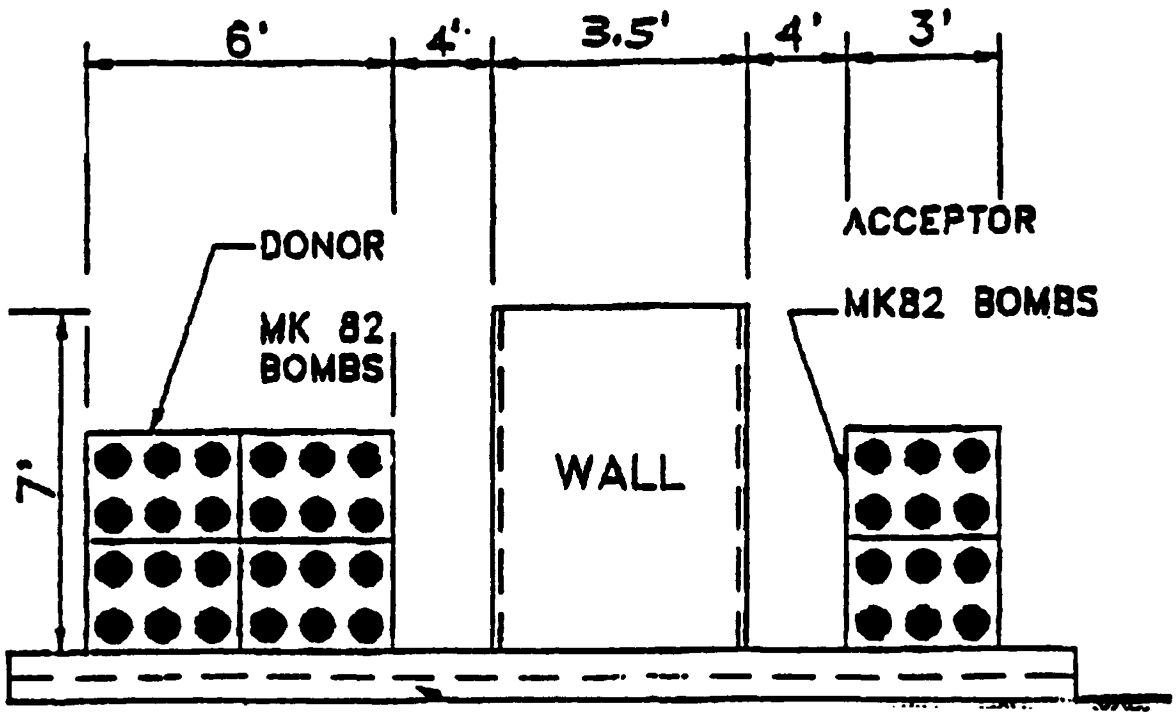

Figure 1. Geometry of Problem Analyzed.

The problem was divided into three phenomenological regions with different governing parameters and modeling considerations. The first regime considered included the donor and the donor surface of the sand wall. It was desired to describe the time resolved spatial distribution of pressures incident on the wall. The time resolution was important because sand is a dispersive medium and absorbs high frequency elements of the incident wave which promote damage. Low frequency components however propagate through the wall with minimal attenuation. The spatial distribution of incident pressures is also important since they are intense and highly non-uniform. This suggests that the environment cannot be sustained by merely increasing the flexural rigidity of the intervening wall.

The second problem regime includes the wall response. Specifically, it is desired to describe the physical state of the wall at the time of acceptor interaction and the distribution of particle velocities through the wall. It will be shown that at the time of acceptor interaction the wall is highly fluidized and only the loads promoted by a small portion of the wall near the donor surface actually couple to the acceptors.

The final problem regime which has only been superficially addressed in the subject effort includes the loads promoted by the interaction of the multiphase flow of wall debris and combustion by-products around the acceptors and the acceptor response. The significant parameters in this problem regime include the particle inertia of the wall debris and the relative velocity between the wall debris and the acceptor surfaces.

Loads Associated with Donor: Influence of Stacking Configuration

In order to describe the influence of stacking configuration. numerical experiments were conducted using the AUTODYN® code. The effort began by predicting loads at a two-foot standoff from the explosive stack for single bomb detonations in free air. The detonations corresponded to different locations in the donor stack. The AUTODYN predictions corresponded very closely with cube root scaling.

In the next series of analysis, two cases involving simultaneous detonation were considered. The first case involved two Mk82 bombs stacked parallel to the ground. The second case involved two Mk82 bombs stacked perpendicular to the ground. The pressures promoted in both cases were evaluated at the same locations as in the previous single bomb detonations. The single bomb results, at locations corresponding to the bombs in the two bomb stacks, were then superimposed and compared to the two bomb results. In general, a substantial deviation was seen for the simultaneous detonation of two bombs versus superposition of single bomb results at corresponding locations and times.

In the case of two Mk82 bombs stacked perpendicular to the ground, due to the occurrence of jetting, the predicted pressures sixteen inches above the ground and two feet away from the leading edge of the donor stack were a factor of 2-1/2 greater and the predicted impulse was 60% greater than the corresponding superposed single bomb results (See Figure 2).

In the case of two bombs stacked parallel to the ground and simultaneously detonated; the resulting pressure history is almost the same as the pressure history obtained from detonation of a single bomb corresponding to the column in the donor stack closest to the wall. This suggests that the bomb in the parallel array located farthest from the wall contributes only minimally to the loads at the wall location. Similarly, the impulse obtained by superposition of the single bomb results is about 25% greater than the corresponding two bomb simultaneous detonation (See Figure 3).

Results analogous to the two cases above were obtained for single and multi-column stacking configurations; i.e., the impulse-time histories in the vicinity of the wall location for a single column and multi-column donor are identical for the first several hundred μsec (See Figure 4). During this interval, the impulse and pressure distribution on the wall in entirely dictated by the donor column closest to the wall; i.e., the effect of adjacent donor columns is not evident.

The reason for this is suggested by the fact that at a prescribed distance along the ground, the point in time where the single and multi-column solutions bifurcate is the same at all elevations above the ground. This means that the effect occurs due to interactive effects at the explosive source as opposed to effects associated with propagation of the blast wave. When the donor model is executed in an interactive mode, rarefied regions are seen to occur between columns of the donor bombs. Pressure pulses cannot be propagated across these regions while they exist. The elapsed times during which these regions exist agree with the time intervals during which the single and multi-column results coincide and the pressure levels in directions perpendicular to the ground are correspondingly intensified.

The loads incident on the sand wall from the simultaneous detonation of 24 Mk82 bombs consist of low and high frequency components with spatial distributions that are highly non-uniform. The peak pressure and maximum specific impulse associated with the incident wave is about 11 Kb and 1.5 Mtaps respectively. These maximums occur at ground level.

Wall Response

The sand wall is a dispersive medium which means that it absorbs the energy associated with the high frequency components of the incident wave whereas the low frequency components propagate through the wall relatively unattenuated with their original pulse shape.

Figure 5 shows the attenuation of a prescribed isosceles triangular pressure pulse imposed on the donor surface of the sand wall. The peak pressure (20Kb) and shape of the prescribed pulse is identical however the pulse width is an order of magnitude different (200 μsec and 2 msec). With the exception of hydrodynamic attenuation near the acceptor surface of the wall, the 2 msec pulse manifests very little attenuation as it propagates through the wall. The 200 μsec pulse is severely

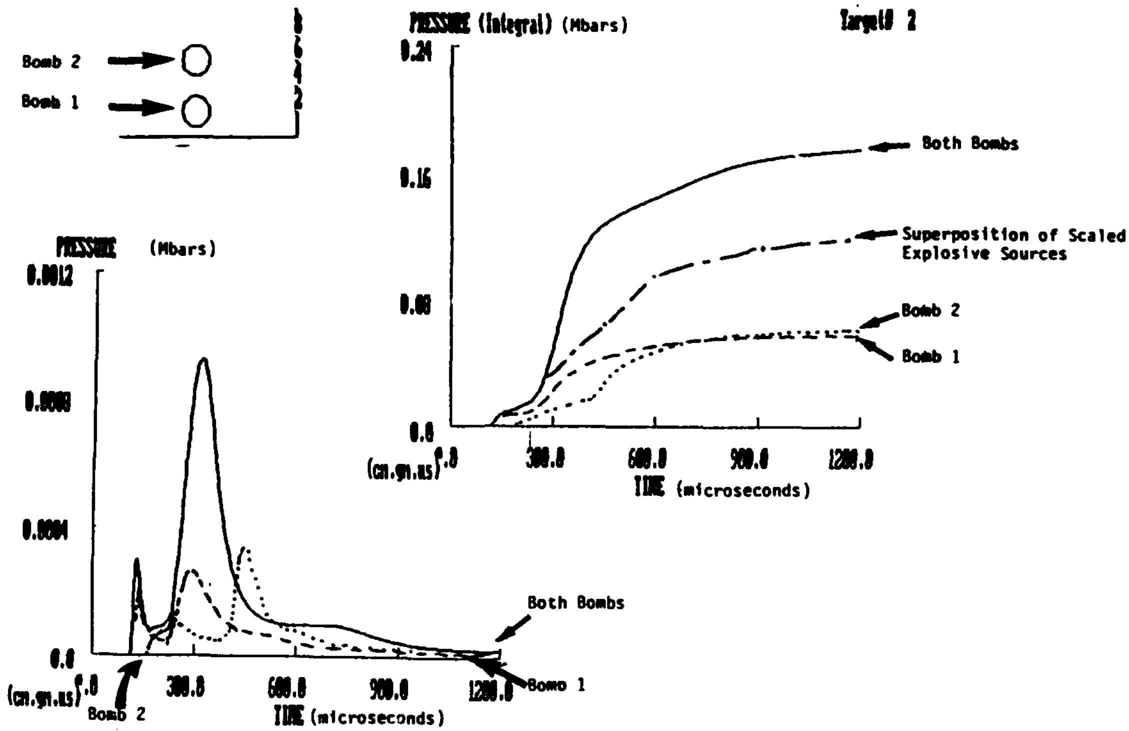

Figure 2. **Pressure and Impulse Associated with Detonation of Two Mk82 Bombs Stacked Perpendicular to Ground Compared with Superposition of Single Bomb Detonations at Corresponding Locations**

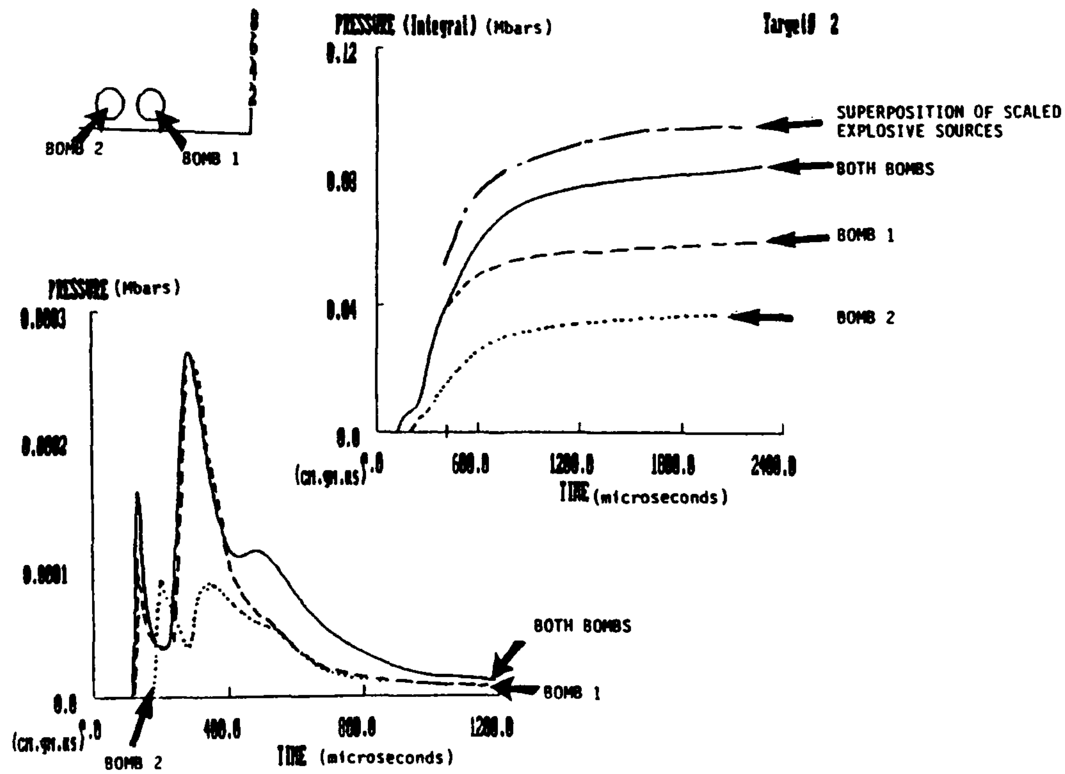

Figure 3. ***Pressure and Impulse Associated with Detonation of Two Mk82 Bombs Stacked Parallel to Ground Compared with Superposition of Single Bomb Detonations at Corresponding Locations***

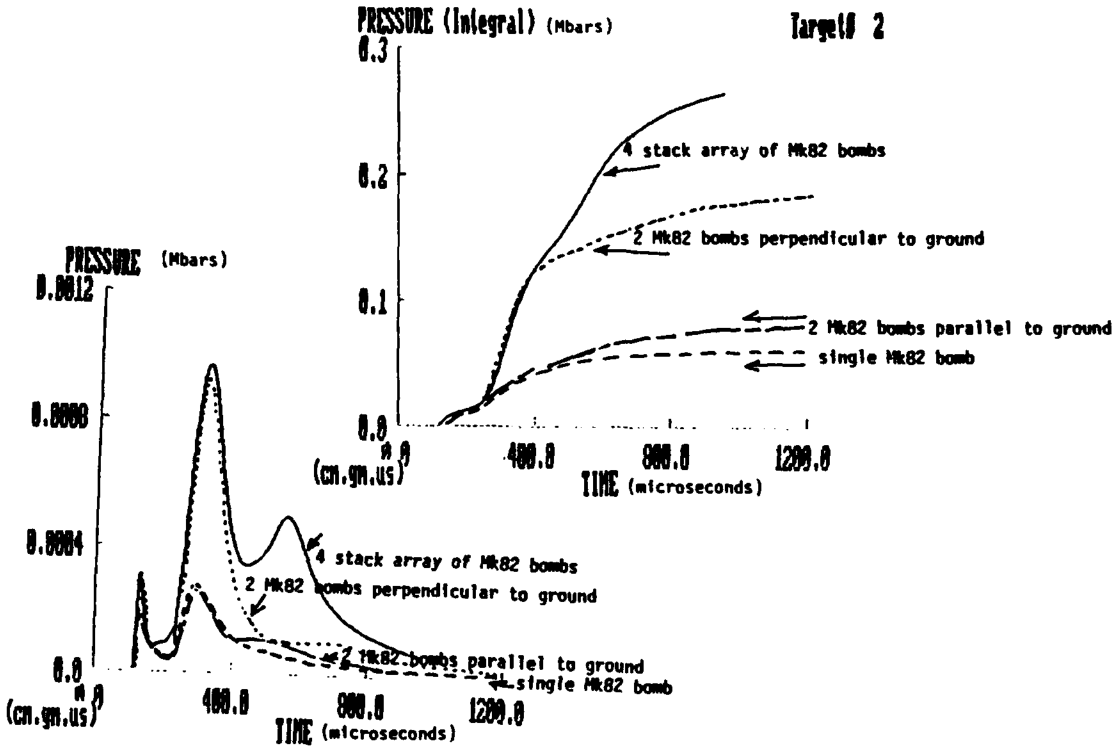

Figure 4. Impulse Histories Associated with single bomb, 1 by 2, 2 by 1, and 2 by 2 Arrays.

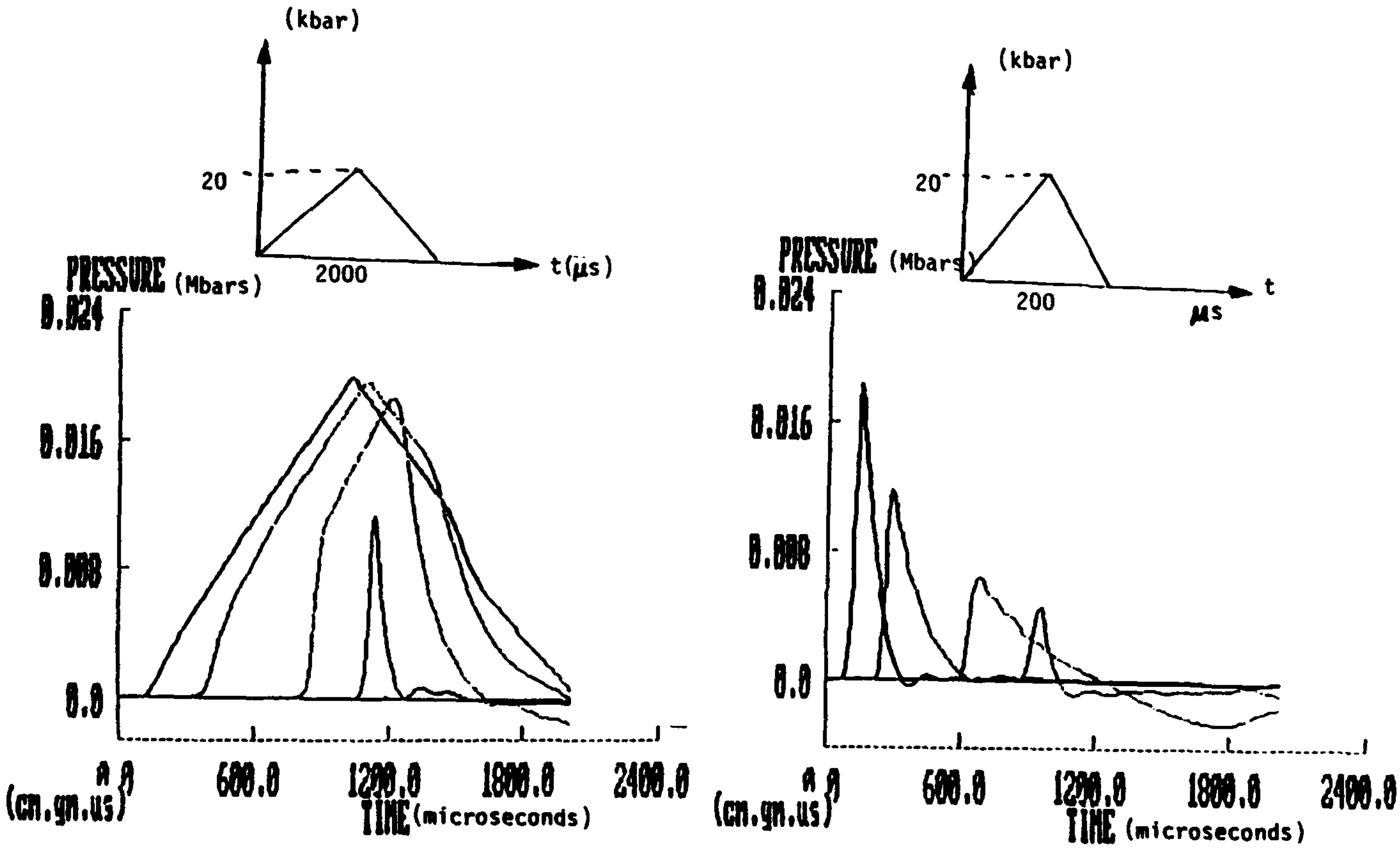

Figure 5. Attenuation of 200 µsec and 2 msec Prescribed Pulse Through Sand Wall

attenuated however with a pulse width that gets wider (with the exception of hydrodynamic attenuation near the acceptor surface) as it propagates through the wall.

The Equation Of State (EOS) employed for sand was developed to simulate 40% porosity dry quartz sand. The model assumes that the cohesive strength of the sand is negligible at pressure levels of interest. Sand also has a very small Gruneisen parameter which is ignored. The EOS is therefore simply a piecewise continuous pressure versus consolidation relation. The virgin loading curve is described by a small elastic segment up to 0.05 Kb. The elastic segment is then followed by two linear crushing regions. At pressures of 17.6 Kb the sand is assumed to be completely consolidated and the loading follows the quartz Hugoniot.

In Figure 6 the peak contact pressure resulting from the collision of a sand wall, imparted with a prescribed rigid body velocity, and a perfectly rigid boundary is considered. The one dimensional solution of this problem for contact pressure, P, is the product of ρcv; where "ρ" is the density , "c" is the sound speed, and "v" is the incident velocity of the wall. In this problem "v" is identical to the particle velocity since the wall is moving as a rigid body. The contact pressure as a function of particle velocity must be bounded by the density and sound speed for the initial state of the sand and the density and sound speed of quartz which corresponds to the final consolidated state of sand. In Figure 6 it can be seen that the corresponding AUTODYN solution for this problem lies between these two bounds. Further, the AUTODYN solution appears to originate on the curve corresponding to the initial state of sand and at higher particle velocities begins to approach the curve corresponding to the final state of sand. Figure 6 also shows the case of the explosively propelled sand wall where the particle corresponding to the acceptor side of the wall (which is also the peak particle velocity in the wall) is used.

Figure 7 shows the impulse corresponding to the cases evaluated in Figure 6. Note that although the peak pressures for the explosively propelled wall appear consistent with the corresponding rigid body formulations, the impulse is not. Rigid body motion of the sand wall results in a uniform distribution of particle velocities through the wall and a square pulse with a pulse width equal to the acoustic transit time through the wall upon contact with the boundary. In the case of the explosively propelled wall however the distribution of particle velocities is highly non-uniform resulting in a triangular pulse with a much shorter pulse width. Due to the fact that about 2/3 of the wall has fluidized prior to impact, a region of only about 10 cm in thickness from the acceptor surface contributes to the development of the pressure pulse. This region also manifests material densities that are about four times as great as the interior of the wall which only has 40 to 50% of its original material density. In comparing the explosively propelled and equivalent rigid body motion of the wall; similar peak pressures are obtained due to the similar physical state and velocity of the acceptor surface. There are significant differences however in terms of the impulse promoted which is largely due to differences in the physical state and particle velocity distribution through the remainder of the wall material.

In the case of a low frequency pulse incident on a sand wall, the particle velocity distribution is almost linear through the wall (See Figure 8). Note also that prior to interaction with the acceptor the particle velocity is maximum on the acceptor side of the wall.

At first look, this is surprising since: (1) The incident pressures are greater on the donor side of the wall than the acceptor; and, (2) The particle velocities on the donor side of the wall are subject to acceleration from the incident pulse for a longer interval of time than particles on the acceptor side of the wall. This is because it takes about 1.7 msec for the incident pulse to propagate from the donor to the acceptor surface of the wall. The particles on the donor surface of the wall are therefore subject to a more intense acceleration from the incident pulse for at least 1.7 msec longer than the particles on the acceptor surface of the wall.

On further consideration however, if we consider the one dimensional analog of the wall response

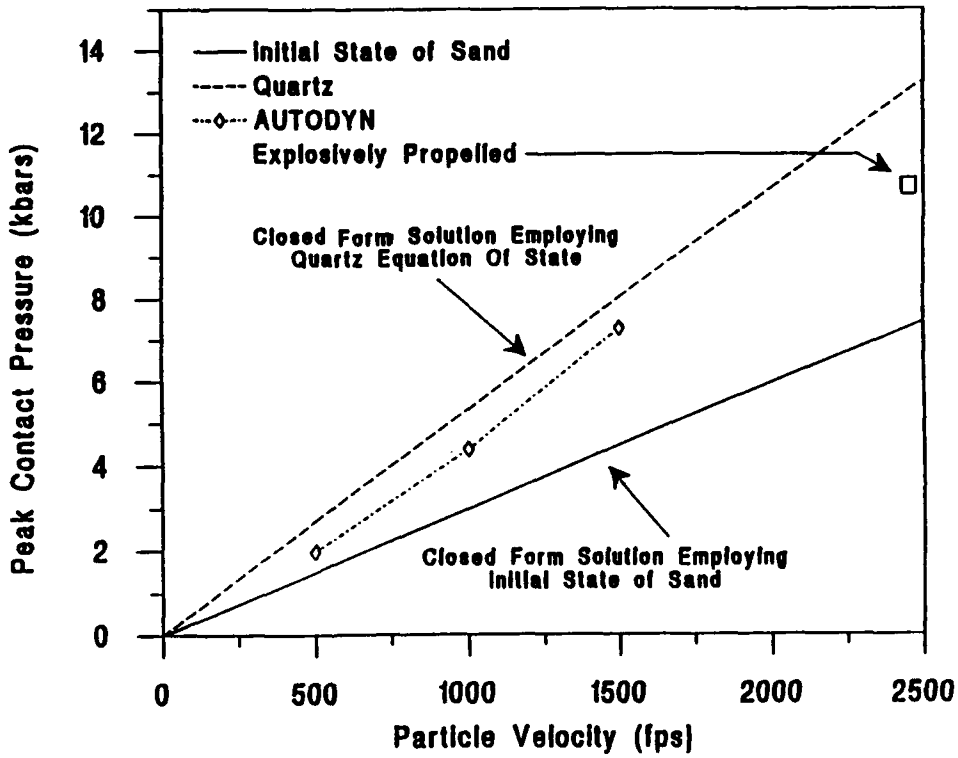

Figure 6. Peak Contact Pressure for a Sand Wall Impacting a Rigid Boundary as a Function of Particle Velocity.

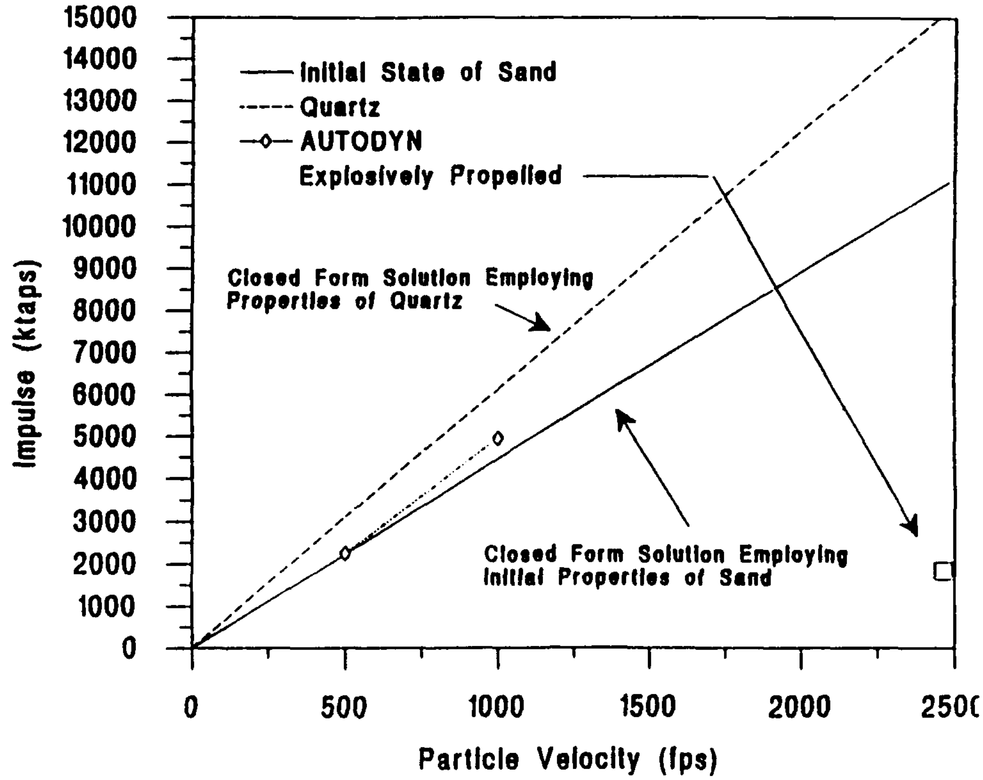

Figure 7. Impulse for a Sand Wall Impacting a Rigid Boundary as a Function of Particle Velocity

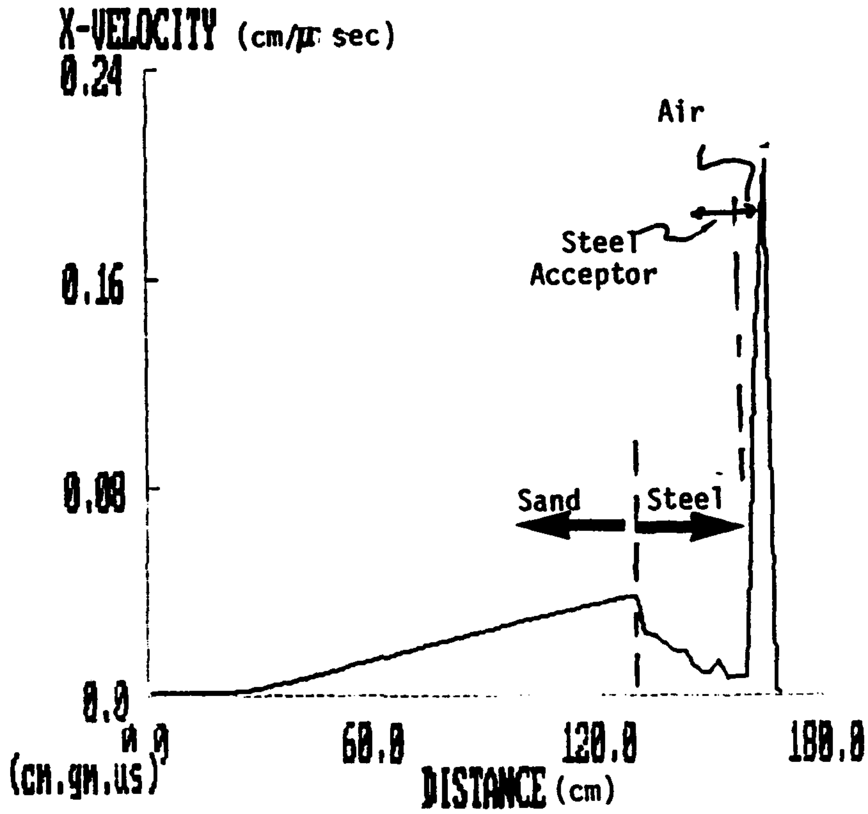

Figure 8. **Particle Velocity as a Function of Distance from the Original Location of the Donor Surface of the Wall for a Prescribed Low Frequency Pulse.**

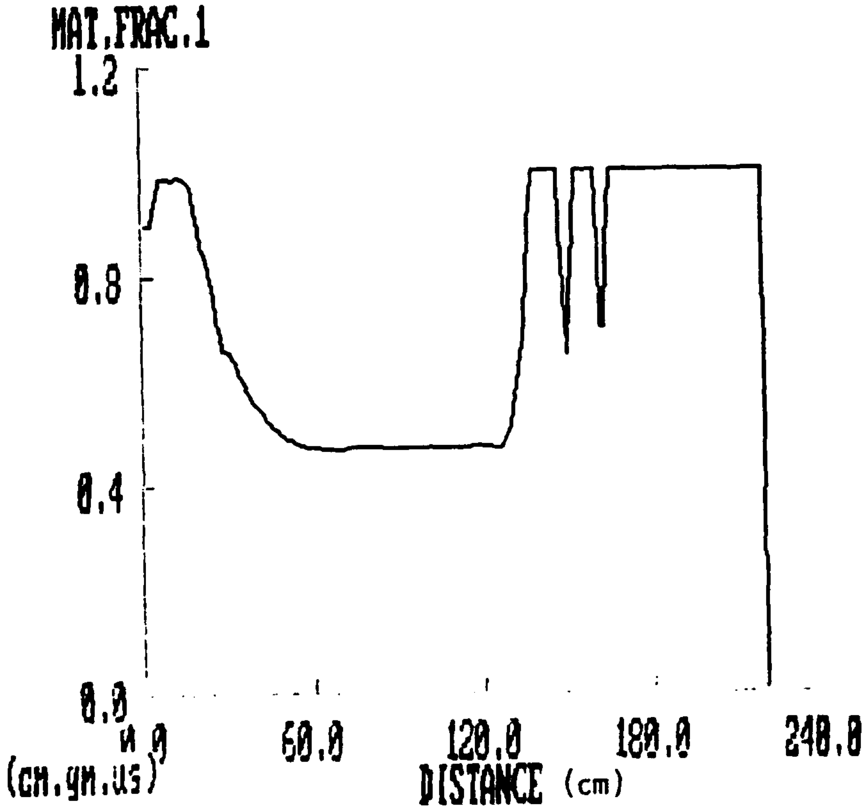

Figure 9. **Material Fraction as a Function of Distance from the Original Location of the Donor Surface of the Wall.**

in terms of an array of linear springs and lumped masses in series (parallel to the floor): the particles on the donor surface of the wall are initially accelerated and impact particles further in the wall. The particles located deeper into the wall however have a much greater associated inertia. This is due to the fact that the remaining thickness of the undisturbed wall has not been fluidized and is resisting the motion of the incident particles. The incident particles are therefore decelerated and the impacted particles gradually accelerate as this process is repeated for the duration of the pulse.

As the pulse propagates through the wall however, the remaining thickness of undisturbed wall material encountered by the pulse decreases. That is, as the pulse approaches the acceptor side of the wall, the inertia of the undisturbed wall material is significantly less than the inertia associated with wall material on the donor side of the wall. Hence, given that a low frequency pulse is only minimally attenuated as it propagates through the wall, the particles on the acceptor side of the wall, after the first transit of the incident pulse through the wall always manifest higher particle velocities than on the donor side of the wall. The linearity of the particle velocity distribution shown in Figure 8 through the wall material also suggests this mechanism since the mass inertia associated with the wall should decrease linearly with wall thickness.

The mechanism described above is associated with low frequency loadings where the constituent wall material has sufficient time to respond to the incident pulse. The wall response is fundamentally different in the case of imposed high frequency pulses where the pressure wave propagates faster than the sound speed of the material and is absorbed close to the donor surface of the wall. In this case, the material cannot respond to the incident loading and discontinuities; i.e., shock waves, are propagated into the material. The particle velocity distribution in the case of shocked materials is influenced by the *particle inertia* of the wall material (as opposed to the *wall inertia* for low frequency pulses) and generally attenuates with shock propagation distance.

For the case of a frequency spectrum consisting of both high and low frequency components the resulting particle velocity distribution will be highly non-uniform depending on the relative proportion of high and low frequency components and the dispersive character of the wall material.

In the case of the Mk82 donor scenario employing a finite tensile strength for the sand wall material, immediately prior to impact (which occurs at about 2.7 msec), a rarefied region begins to form 10 to 20 cm behind the acceptor side of the wall at about 2.1 msec. This occurs due to the incident compressive wave reflecting from the acceptor free surface of the wall in tension.

When the wall contacts the acceptors, a compressive pulse is transmitted into the acceptors and into the wall material. The pulse propagates through the acceptor and reflects in tension from the acceptor free surface. This tensile pulse then propagates back to the wall-acceptor interface. This tensile pulse superimposes on the incident compressive pulse reducing the magnitude evident at the wall-acceptor interface.

The reflected tensile pulses transmitted back into the sand material from the acceptor enhance the spallation process already under way in the acceptor side of the wall. The waves trapped in the remainder of the wall continue to generate new tensile fields from newly formed free surfaces associated with the spall planes. The spalled material starts moving with a constant acceleration but disperses in several directions and is enhanced by additional spall planes which occur in orthogonal directions.

This is particularly evident in the middle third of the sand wall which has 50% of the initial density of sand (see Figure 9). This is as compared with the donor and acceptor sides of the wall which are significantly compressed by up to a factor of 1.5 to 2 over the initial sand wall density. The stress waves within each spall plane "ring" which eventually mitigates the residual stress in each plane.

The spall planes from the first 10 to 30 cm of the acceptor side of the wall couple to the acceptor and is the major contributor to the impulse incident on the acceptor. The specific impulse associated with the highly dispersed material in the middle of the wall is very low and produces a much lower response in the acceptor. Eventually the acceptor moves faster than the residual wall material so that the remaining regions on the donor side of the wall never couple to the acceptor.

This material spreading due to spalling reduces the impact loads on the acceptor since the momentum per unit area decreases during this process. Thus, for the case of a sand wall, an increased standoff should exponentially reduce the acceptor loads. It should be noted that a tensile strength of 1000 psi was used in the sand wall models and is highly uncertain.

As the tensile strength of the sand wall approaches zero however the thickness of the spall planes should decrease eventually to the diameter of individual particles and the tensile field developed in the wall becomes negligible. Under these conditions, the environment at the acceptor resembles a continuous flow of sand material and the physics of the interaction change.

Figure 10 shows the time history of the incident pressure on cylindrical steel acceptors from a sand wall with negligible tensile strength subject to a prescribed low frequency loading. In Figure 10 the prescribed load is superimposed on the pressure history incident on the acceptor. The prescribed load represents a specific impulse of about 3.6 Mtaps. The corresponding specific impulse incident on the acceptors is about 1 Mtap and represents a reduction of about 72% from the donor environment incident on the sand wall.

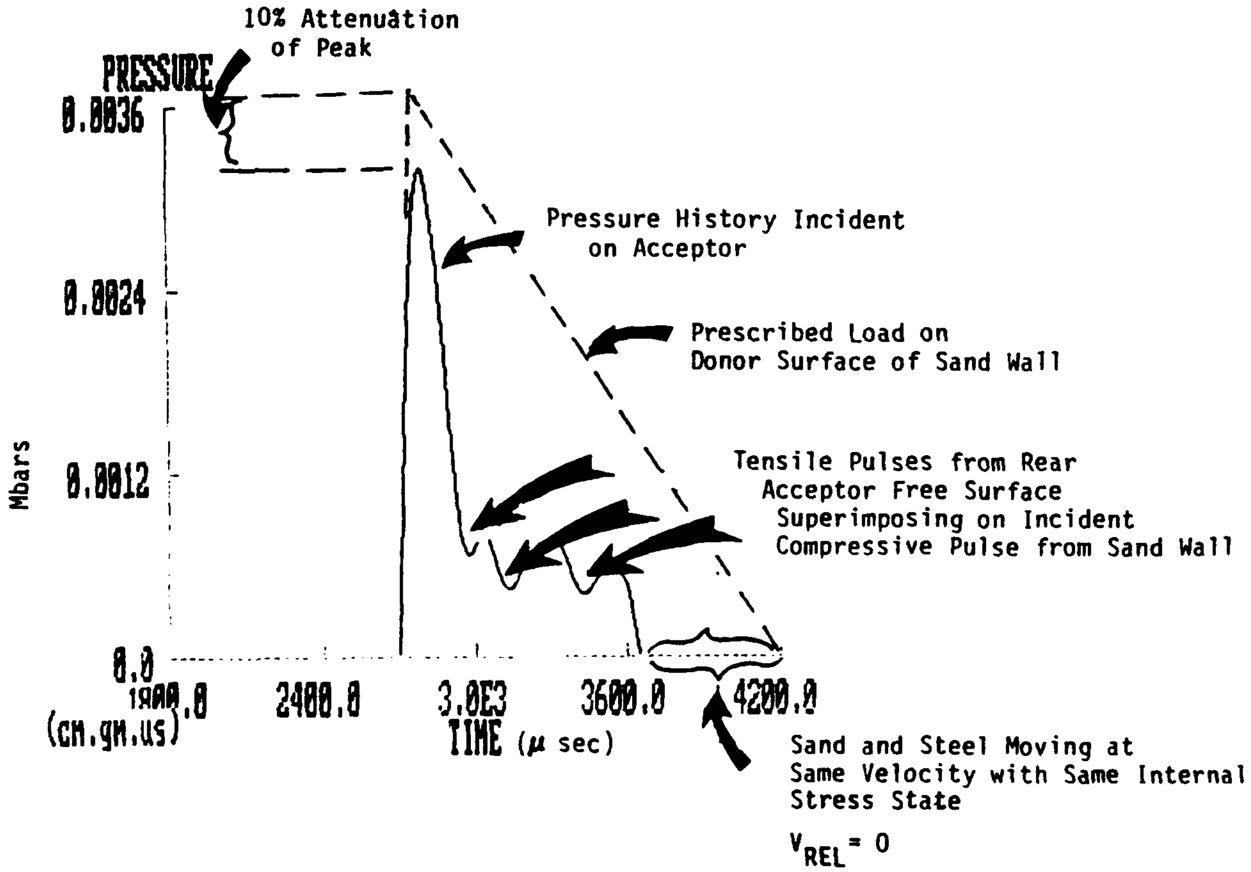

Figure 10. Pressure-time History Incident on Acceptors from a Prescribed Low Frequency Pulse

In Figure 10 the peak pressure has been attenuated by about 10% from the level incident on the cell wall. This attenuation is due to the dispersive characteristics of the sand. If the pulse were 2 msec instead of 1.8 msec, no attenuation would be observed. Similarly, if the rise time associated with the prescribed pulse was 20 instead of 150μsec, severe attenuation of this peak pressure would occur.

The modulation of the pulse after the initial compressive peak in Figure 10 is due to the incident compressive pulse reflecting in tension from the rear free surface of the acceptor. The local maxima in Figure 10 associated with this modulation occurs at intervals of 240 to 260 μsec. This elapsed time corresponds to twice the transit time in the deformed configuration of steel acceptor plus the arrival time in the sand wall.

The pulse incident on the acceptor ends when: (1) The relative velocity of the sand wall material in contact with the acceptor approaches zero -- see Figure 11; and, (2) The ringing in the steel acceptor stops due to an equilibrium stress state occurring in the sand wall material and the acceptor such that no pressure is transmitted or reflected at the wall material-acceptor interface -- see Figure 12.

Figure 11 shows the particle velocity distribution at the conclusion of the incident pulse on the acceptor. The particle velocities are plotted as a function of distance from the donor surface of the wall. At least four discrete regions can be identified on the plot. The first region on the donor side of the wall (which consists of approximately 46 per cent of the original wall thickness and mass) consists of consolidated wall material (see Figure 9). This material has a particle velocity considerably less than the acceptor or wall material in contact with the acceptor and therefore this portion of the wall material never couples to the acceptor.

This consolidated region exists because of the mechanism hypothesized previously which promotes high particle velocities on the acceptor side of the wall in the presence of low frequency load functions. That is, during the relatively long elapsed time that the donor side of the wall is subject to the incident compressive pulse, the sand particles on the donor side of the wall are accelerated and impact the undisturbed wall material. Due to the much larger inertia of this undisturbed wall material, the impacted wall region resists the motion of the particles incident from the donor side of the wall. The incident sand particles from the donor side of the wall are therefore decelerated. The only mechanism available to decelerate these sand particles is through an equal and opposite reaction force which opposes the motion of the sand from the donor side of the wall (this is the reason for the springs in the lumped mass-spring analog previously described). At the same time that this equal and opposite reaction force is generated inside the wall, the donor surface of the wall is still being compressed. Hence a consolidated region exists on the donor side of the wall as shown in Figure 9.

A second region, representing the mass equivalent of approximately 35 to 40 cm of the original wall material is also seen to extend from the consolidated region to about 120 cm at the time the pulse ends. This region which consists of highly fluidized and dispersed sand has about 40 to 50 per cent of the original sand wall material density and cannot sustain any pressure (see Figure 9). Some fraction of this region may couple to the acceptor however due to the low particle velocities, material densities, and non-existent residual stress associated with this region; the contribution of this region to the loads promoted on the acceptor is insignificant.

A third region is evident in Figure 9 which consists of planes of consolidated wall debris separated by planes of highly rarefied material. These rarefied regions are the result of ringing in the acceptor which has propagated into the sand. This region represents about 15 to 20 cm of the original sand wall thickness and mass and is the major contributor to the impulse promoted on the acceptor.

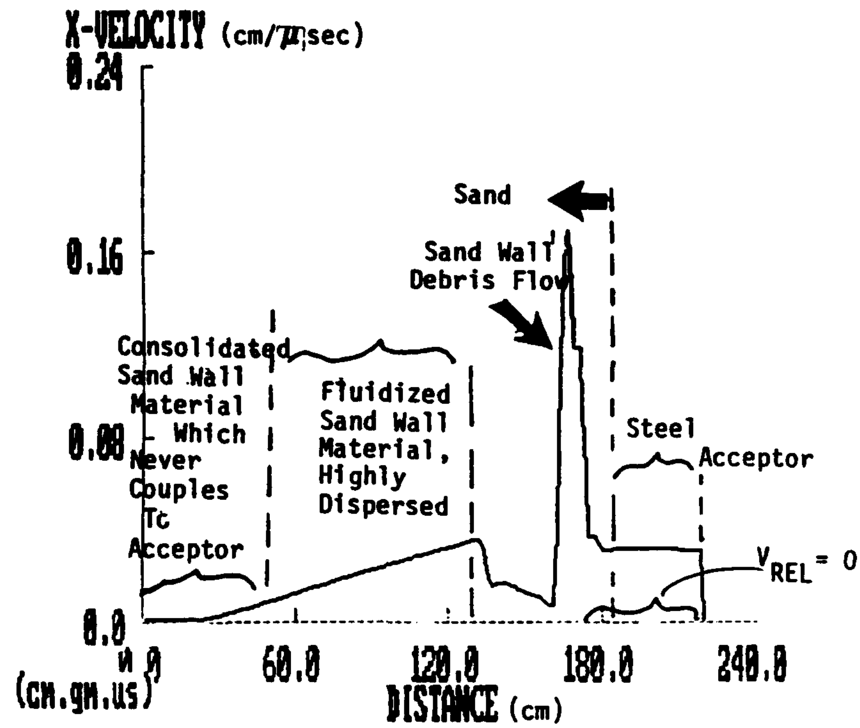

Figure 11. Particle Velocity Distribution at the Conclusion of the Pulse Incident on the Acceptor.

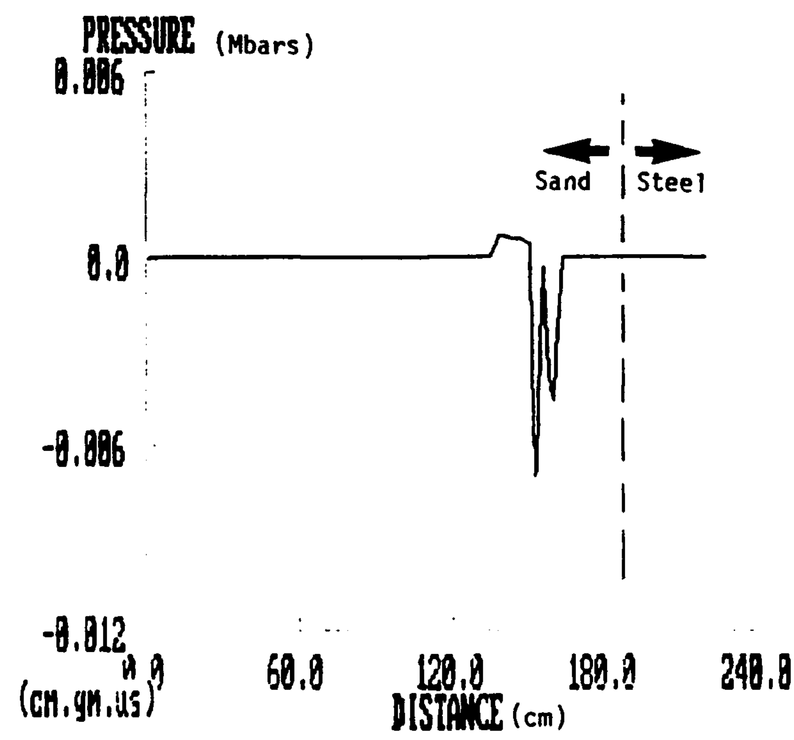

Figure 12. Pressure as a Function of Distance from the Donor Surface of the Sand Wall at the End of the Incident Pulse on the Acceptor.

Finally, there is also seen in Figure 9 a buildup of consolidated sand wall debris in front of the acceptor that is moving at the same velocity as the acceptor (see Figure 11). As is evident from the flat particle velocity profile through the acceptor and the sand wall material in this region (see Figure 11), both the acceptor and residual sand wall debris are now moving at a rigid body velocity of approximately 1300 fps. At this point, the pressure in the acceptor surface of the sand wall and the acceptor are in equilibrium and no additional stress is transmitted (see Figure 12). The incident pulse on the acceptor therefore ends.

For comparison purposes, the peak contact pressure and corresponding impulse for a water wall sustaining a prescribed rigid body and explosively propelled impact with a rigid boundary is shown in Figures 13 and 14 (analogous to Figures 6 and 7 for sand). In Figures 13 and 14 the corresponding results for a sand wall have also been superimposed. The water wall manifests higher peak pressures than the sand wall due to the larger impedance (the product of material density and acoustic wave velocity) of water (see Figure 13). The resulting impulse of water (see Figure 14) however is much less than the sand wall. This is due to the smaller particle inertia of the water relative to the sand which allows the water to change direction more easily than sand and flow around the acceptors. This results in a much lower impulse coupling coefficient for the water wall than the sand with a correspondingly smaller impulse promoted on the acceptor.

Recommendations

Given the insight garnered from the analysis above, strategies were evolved that mitigate relevant environmental parameters for each problem region. In the donor region, recessing the floor reduces the impulse on the wall in excess of a factor of 4. For this particular problem the optimum floor recession was seen to be 3 feet.

In the case of the wall response region, three concepts were evolved. First, it was recommended that a contoured high impedance core that enhances particle velocities normal to the ground be incorporated into the wall. Second, layered materials, with mechanical stiffness and masses determined from a lumped mass spring model alluded to above, should be incorporated into the wall in order to achieve favorable particle velocity distributions through the wall thickness. Finally, it was shown that a connection from the wall to the surrounding structure that survives 1 msec. will reduce the impulse on the acceptor by at least 35%. This was estimated from an extremely conservative analysis and it is likely that the benefits of a properly designed connection will greatly exceed this preliminary estimate.

In terms of impulse coupling to the acceptor: minimizing the particle inertia of the wall debris material is desirable. It was also recommended that an N-particle, lumped mass spring model be developed in conjunction with a multilayer shell model to describe the rigid body displacement and non-rigid body deformation of the acceptors. This in turn would allow explicit determination of impulse coupling coefficients for different locations in the acceptor stack.

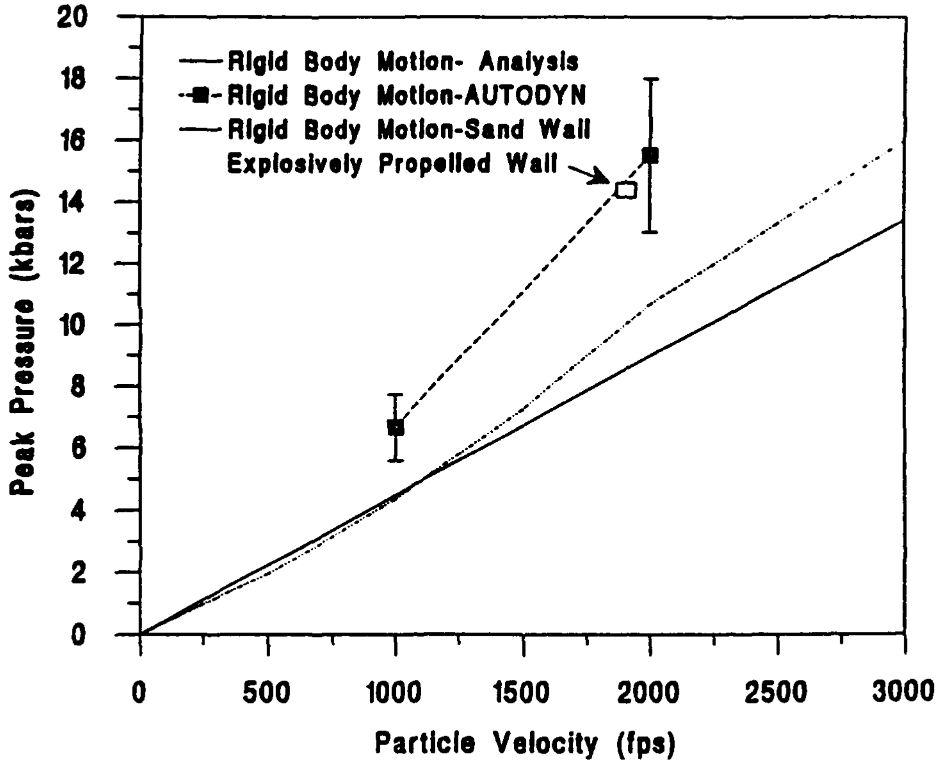

Figure 13. **Peak Contact Pressure for a Water Wall Impacting a Rigid Boundary as a Function of Particle Velocity.**

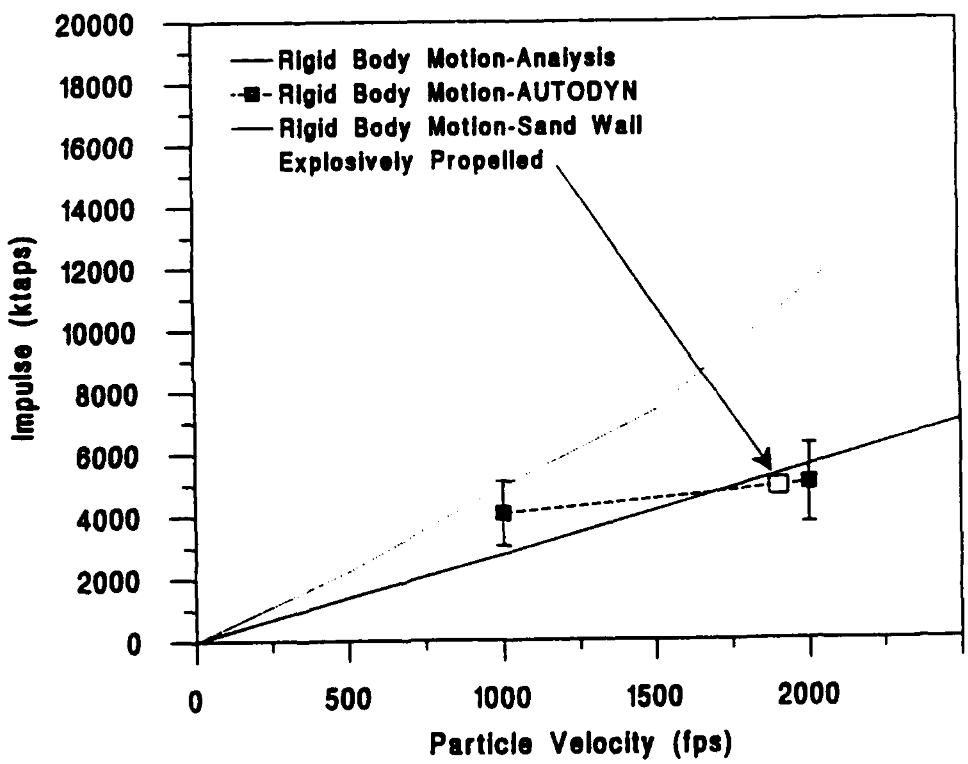

Figure 14. **Impulse for a Water Wall Impacting a Rigid Boundary as a Function of Particle Velocity**

THE REFLECTED IMPULSE ON A CURVED WALL PRODUCED BY A SPHERICAL EXPLOSION IN AIR

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18-20 August 1992, Anaheim, CA.

ABSTRACT

The paper deals with the impulse on a concave wall resulting from the reflection of the spherical blast wave of an explosion in air. This situation arises when a spherical blast wave hits a non-planar surface, such as the wall of a containment vessel. Two types of surfaces are considered, cylindrical and spherical, in addition to the standard plane wall. The work is based on computations with the PISCES two-dimensional flow code, employing second order numerical schemes. The results for the plane surface are compared with the compiled experimental data in the literature. The study was carried out for a 2 Kg TNT charge at a distance of 1 m from the surface, assuming that the radii of the cylinder or sphere are also 1 meter. It was found that the reflected impulse on a cylindrical surface is ≈18% over the plane wall case. For a spherical wall the reflected impulse (for the first shock reverberation) is about 50% over the plane wall impulse.

INTRODUCTION

In designing structures to withstand the effects of explosions, the relevant blast parameter is usually the impulse contained in the pressure pulse, and not the pressure itself. The reason for this is that most structures have a long response time compared to the blast wave duration.

The blast wave parameters for spherical explosions in air was dealt with in many publications. The results were compiled by Baker [1], and Baker et al. [2]. The data in these references comprise also the reflected impulse on a plane wall. In practical problems, however, there is a need for estimating the reflected impulse on a curved wall, such as in designing cylindrical or spherical containment vessels. The present paper aims to obtain an estimate of the reflected impulse on concave walls. Two types of walls are considered in the present paper: cylindrical and spherical. In both cases the charge is assumed to be located at a distance equal to the radius of curvature of the surface. This means that the charge lies along the axis of symmetry, in the case of the cylindrical surface, and on the center, for the spherical surface. (See Fig.1).

The present study is limited to one value of the shock parameter,

$$R/W^{1/3} = 2\ ft/Lb^{1/3}\ (\approx 0.8\ m/Kg^{1/3})$$

where R is the distance from the center of the charge and W is the charge weight. Actually, the calculations were carried out with the following values:

$$R = 1\ m$$
$$W = 2\ Kg\ (TNT)$$

Using the similarity rules for explosions in air (at sea level conditions), we may apply the results of the present calculations to other combinations of R and W according to the relation

$$i/W^{1/3} = f(R/W^{1/3})$$

$$i = \int (P_w - P_o)dt$$

where i is the impulse per unit area of the reflected wave, Po and Pw are the atmospheric pressure and the reflected wave pressure, respectively, and t is the time. It should be stressed, however, that this relation strictly holds for the situation described above, i.e. that the charge is located at the center of the surface, so that R = Rc, where Rc is the radius of curvature. Otherwise, the similarity rule should be modified to take into account the wall curvature. This modified rule would have the form:

$$i/W^{1/3} = f\ (R/W^{1/3},\ Rc/R)$$

THE COMPUTATIONAL MODEL

The solution to the problem is obtained numerically, using the PISCES 2DELK hydrocode [3]. This code has a second order Eulerian processor with a multi- material capability, so that a different equation of state may be employed to describe the ambient air and the explosion products.

The computational model consists of a quadrilateral grid for the cylindrical surface case, and a wedge-like grid for the spherical surface case. (Fig.1). The axis of symmetry and the surface on which the wave is reflected are defined by a "rigid wall" boundary condition. For the plane surface case, a "continuative flow" boundary condition was employed at the open sides of the grid, to minimize edge effects.

The air is described by an ideal gas equation of state, with a specific heat ratio τ=1.4. The explosive charge is approximated by a sphere of dense gas, with τ=1.3. Although this representation of the detonation products is very crude, especially at the high pressure regime, it produces the correct blast wave impulse. This result was verified by varying the equation of state of the detonation products and examining the resulting impulse. Such studies show that although some details of the flow field depend on the equation of state, the impulse is insensitive to it. A similar approach was employed in treating air blasts induced by high explosives in previous works [4,5].

In accordance with the above description, the initial conditions are uniform pressure and density in the entire mesh, except for a small spherical region which represents the high explosive. The initial conditions in the ambient air are:

$$\rho = 1.25 \text{ Kg/m}^3$$

$$p = 0.1 \text{ MPa}$$

and the initial conditions for the detonation products are:

$$\rho = 1600 \text{ Kg/m}^3$$

$$e = 4.1 \text{ MJ/Kg}$$

where e, the specific internal energy of the explosive, was taken from [6].

THE NUMERICAL SOLUTION

The results of the flow simulation will be described in some detail for the plane surface case. The computational grids are shown in Fig.2. In these grids the cell size varies as a geometrical series in both directions. In this way the flow field details are preserved in the early stages of the blast wave formation, when the flow gradients are very large. The grid shown in Fig.2a has a geometric ratio of 1.032, which produces a very fine grid in the vicinity of the origin, so that the charge occupies about seven mesh cells radially. This grid was used up to t = 0.2 ms, when rezoning to the coarser grid of Fig.2b was carried out. The new grid had a geometric ratio of 1.02, and was used to the end of the calculation without further changes.

Fig.3 shows the flow field at t=0.2 ms. The symmetry of the flow is not perfect, due to numerical effects near the axis of symmetry. This asymmetry increases at later times, but the solution is still acceptable since the main objective of the work is the integrated impulse, and the details of the pressure time history do not affect the impulse significantly.

The flow field at t=0.6 ms is shown in Fig.4. At this time the main shock wave has already hit the wall and a reflected wave was created. At later times, (Figs.5 and 6), the reflected wave moves farther from the wall. At t=1.0 ms the pressure near the wall has dropped to about 0.2 MPa (twice the atmospheric pressure), and at t=1.35 ms the pressure is below atmospheric, and no further positive contribution to the impulse is made beyond this time.

The calculations for the other cases were carried out similarly. In fact, the first phase of the blast wave calculation (to 0.2 ms) described above was used to create a starting state for the other cases using appropriate rezoning.

RESULTS AND DISCUSSION

The impulse per unit area on the wall is defined by:

$$i(t) = \int_{o}^{t} [P(t') - P_o]\, dt'$$

The blast wave is characterized by a high peak followed by a quick decay to below atmospheric pressure. The relevant impulse for structural response in most cases is the peak value, which corresponds to positive overpressure.

Fig.7 shows the time history of the impulse for the three cases. The peak pressure is identical for the three types of surfaces, and therefore the curves coincide for early times. At later times, however, the differences in wall curvature affect the local flow, with a corresponding effect on the wall impulse.

For the plane surface, the peak impulse is attained at t≈1.1 ms, about 0.6ms after the shock front arrival. The peak value is 0.80 MPa-ms. This value should be compared with the compiled data of [2], which predict an impulse of 0.87 MPa-ms. The difference (≈8%) is reasonable in view of the scatter in the experimental results.

For the cylindrical surface, the peak impulse is attained somewhat later, at t=1.6 ms. However, about 98% of the peak is obtained at t=1.2 ms. The peak impulse is 0.94 MPa-ms, 17.5% over the plane surface case.

The impulse curve for the spherical case exhibits a different behavior. In this case, due to the spherical symmetry, shock wave reverberations occur between the wall and the origin. The timing is such that the reflected wave from the center hits the wall and contributes further to the impulse, before its "saturation" due to the local flow is completed. In this case it is difficult to define the maximum impulse. For the purpose of comparing with the other cases, one may take the value just before arrival of the reflected wave from the origin. This value is 1.22 MPa-ms, about 53% over the plane surface case, and about 30% over the cylindrical surface case.

CONCLUSIONS

The impulse produced on a curved wall by a spherical explosion in air depends on the local wall curvature. For the special case of explosion at the center of a cylindrical or spherical surface, the following values were obtained using hydrocode calculations,

Plane Surface:	0.80 MPa-ms
Cylindrical Surface:	0.94 MPa-ms.
Spherical Surface:	1.22 MPa-ms.

These values were obtained for a TNT charge of 2 Kg, at a distance of 1 m. They may be extrapolated to other combinations of charge weight and distance according to the well known similarity rule for scaling impulse data, as explained in the introduction.

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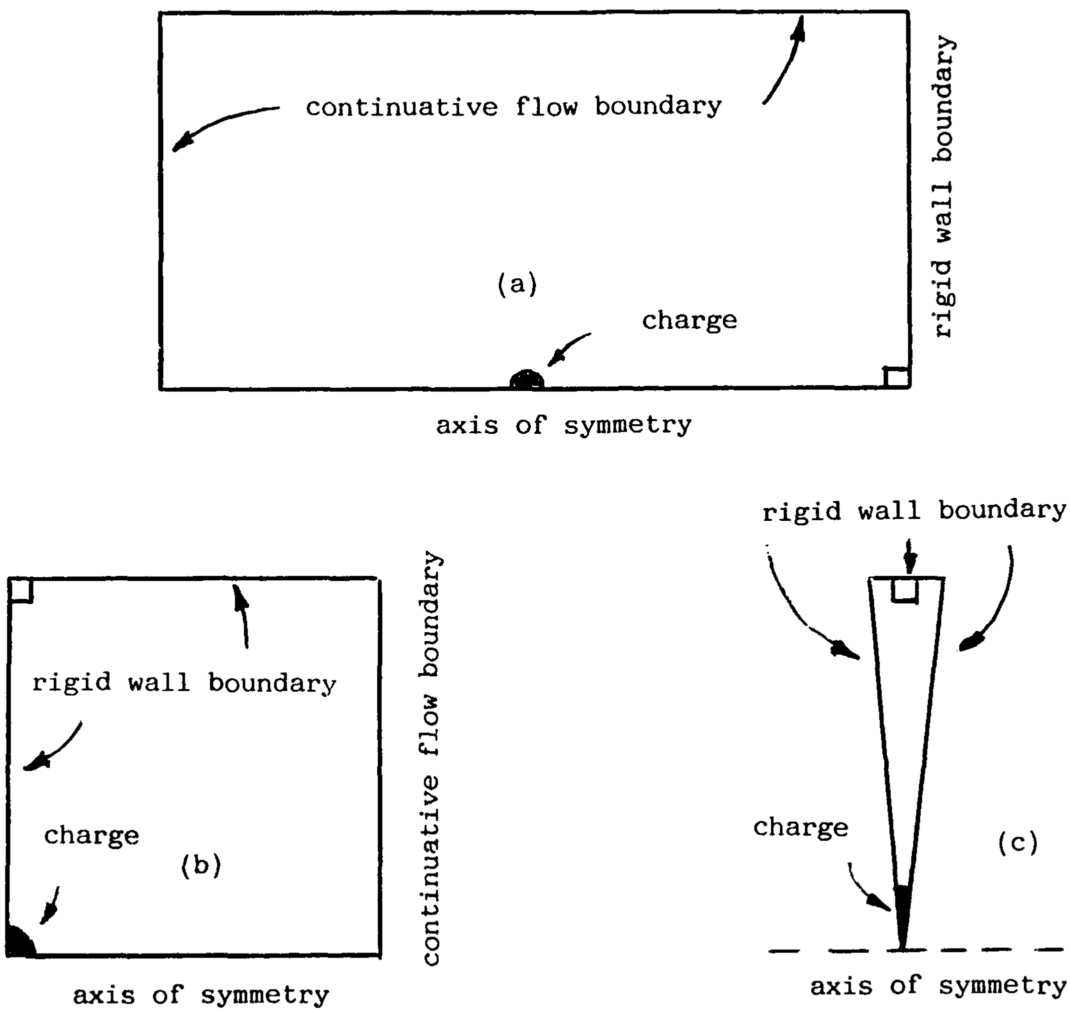

FIGURE 1: COMPUTATIONAL SET-UP FOR THE PROBLEM
(a) Plane Surface
(b) Cylindrical Surface
(c) Spherical Surface

□ location of impulse computation

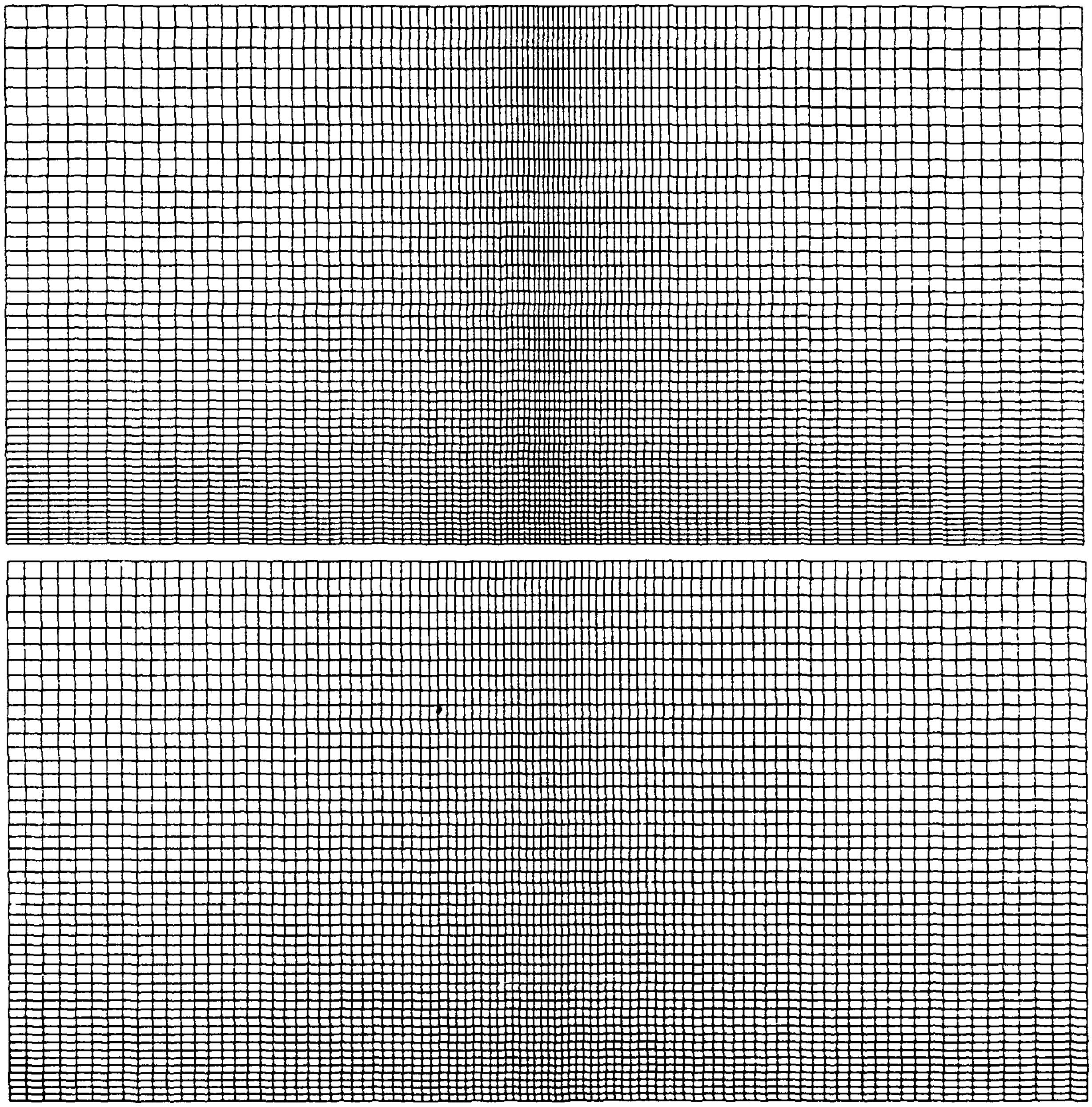

FIGURE 2: THE COMPUTATIONAL GRID FOR THE PLANE SURFACE CASE
Top: The grid for $0 < t < 0.2$ ms. Geometric ratio = 1.032
Botttom: The grid for $t > 0.2$ ms. Geometric ratio = 1.020

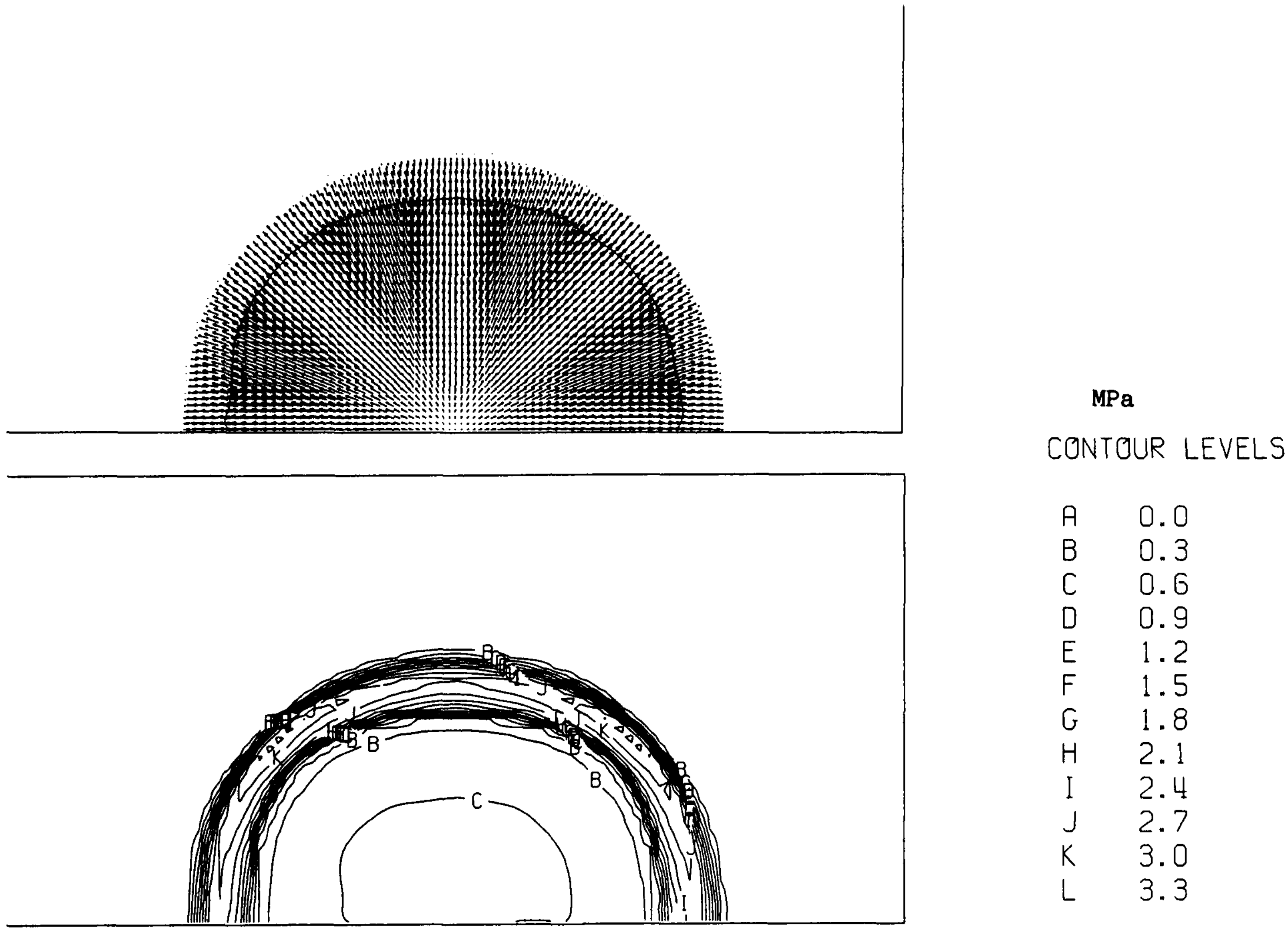

FIGURE 3: VELOCITY VECTOR PLOT AND PRESSURE CONTOURS AT t = 0.2 ms.

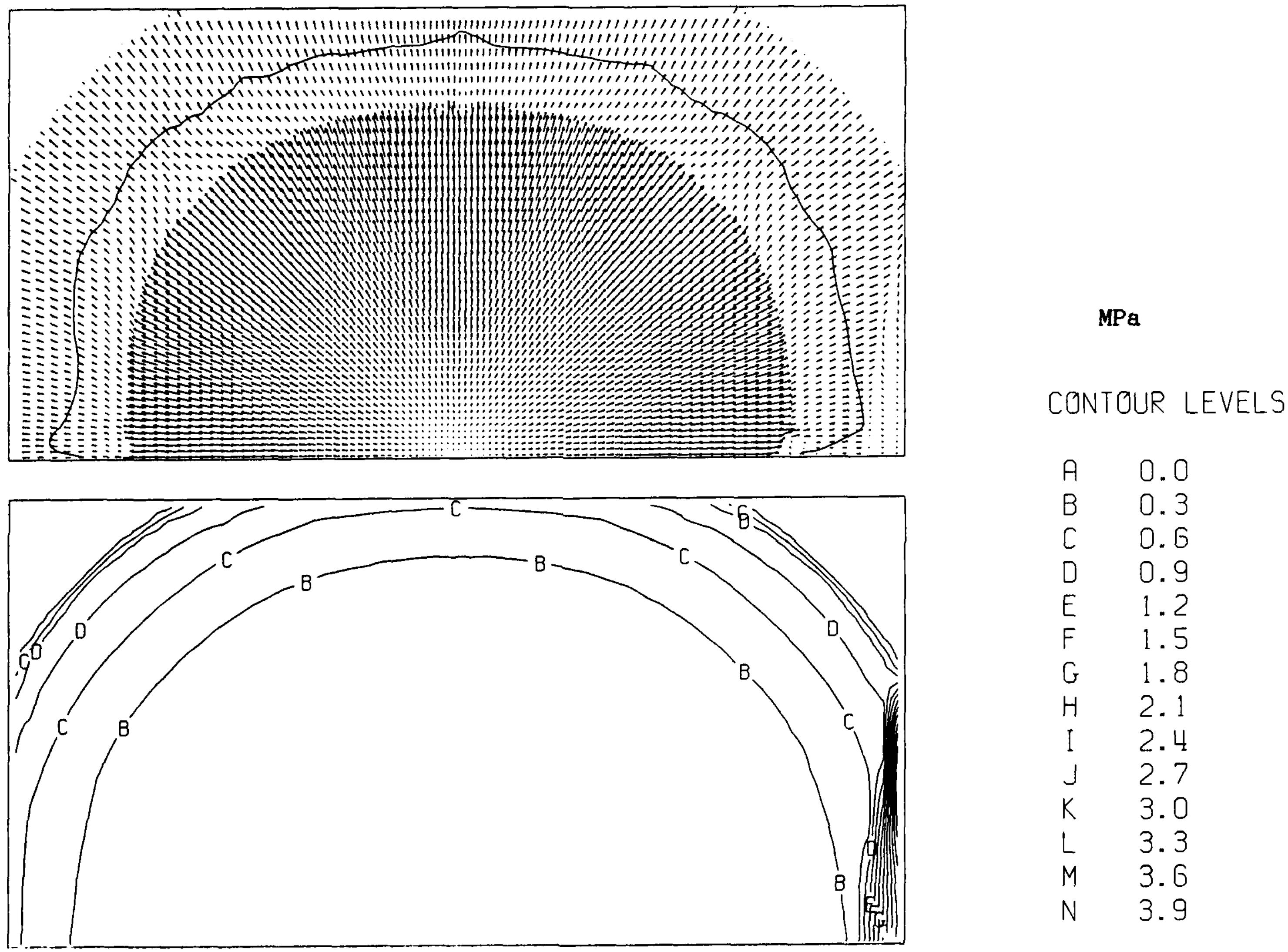

FIGURE 4: VELOCITY VECTOR PLOT AND PRESSURE CONTOURS AT t = 0.6 ms.

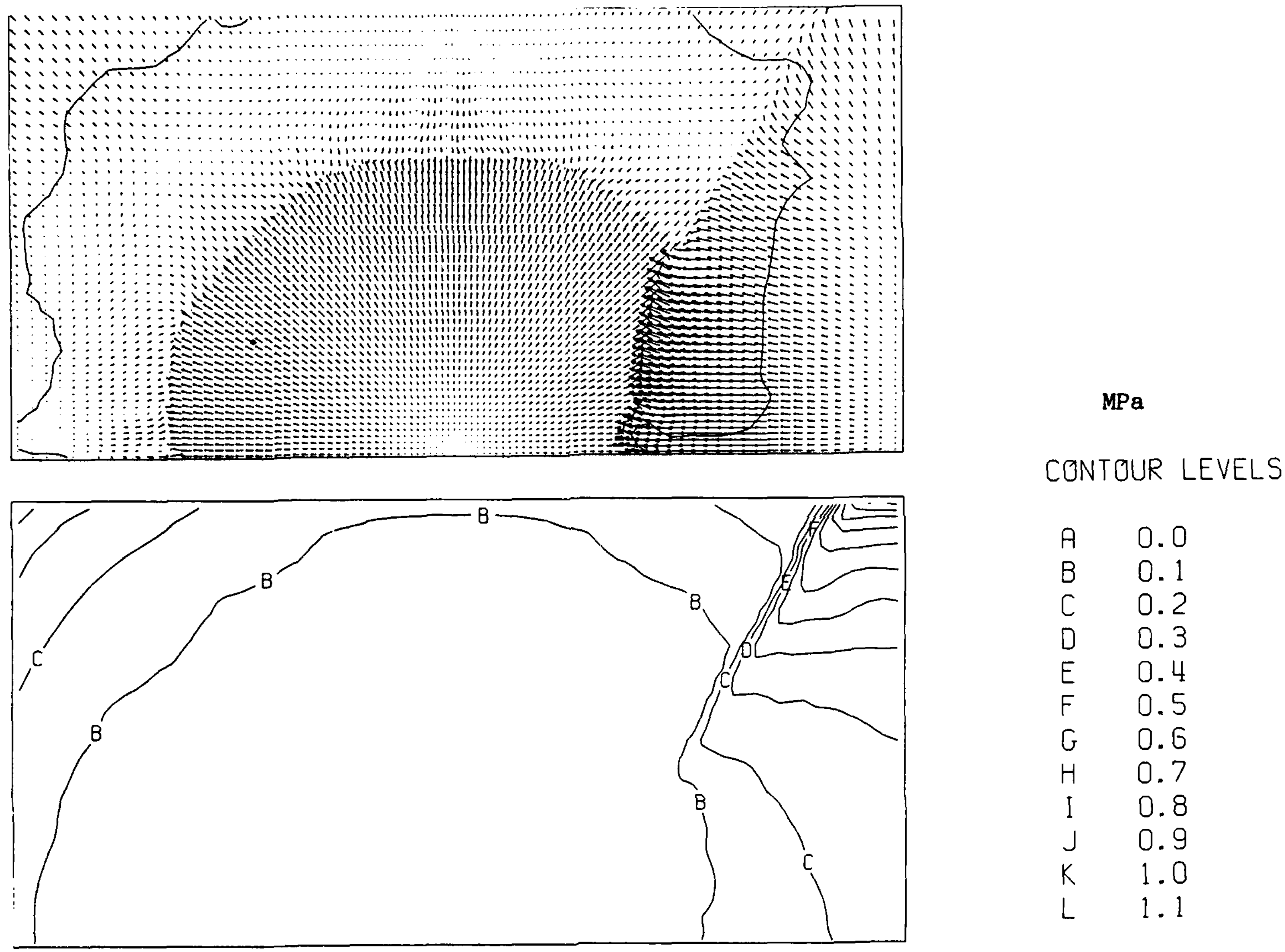

FIGURE 5: VELOCITY VECTOR PLOT AND PRESSURE CONTOURS AT t = 1.0 ms.

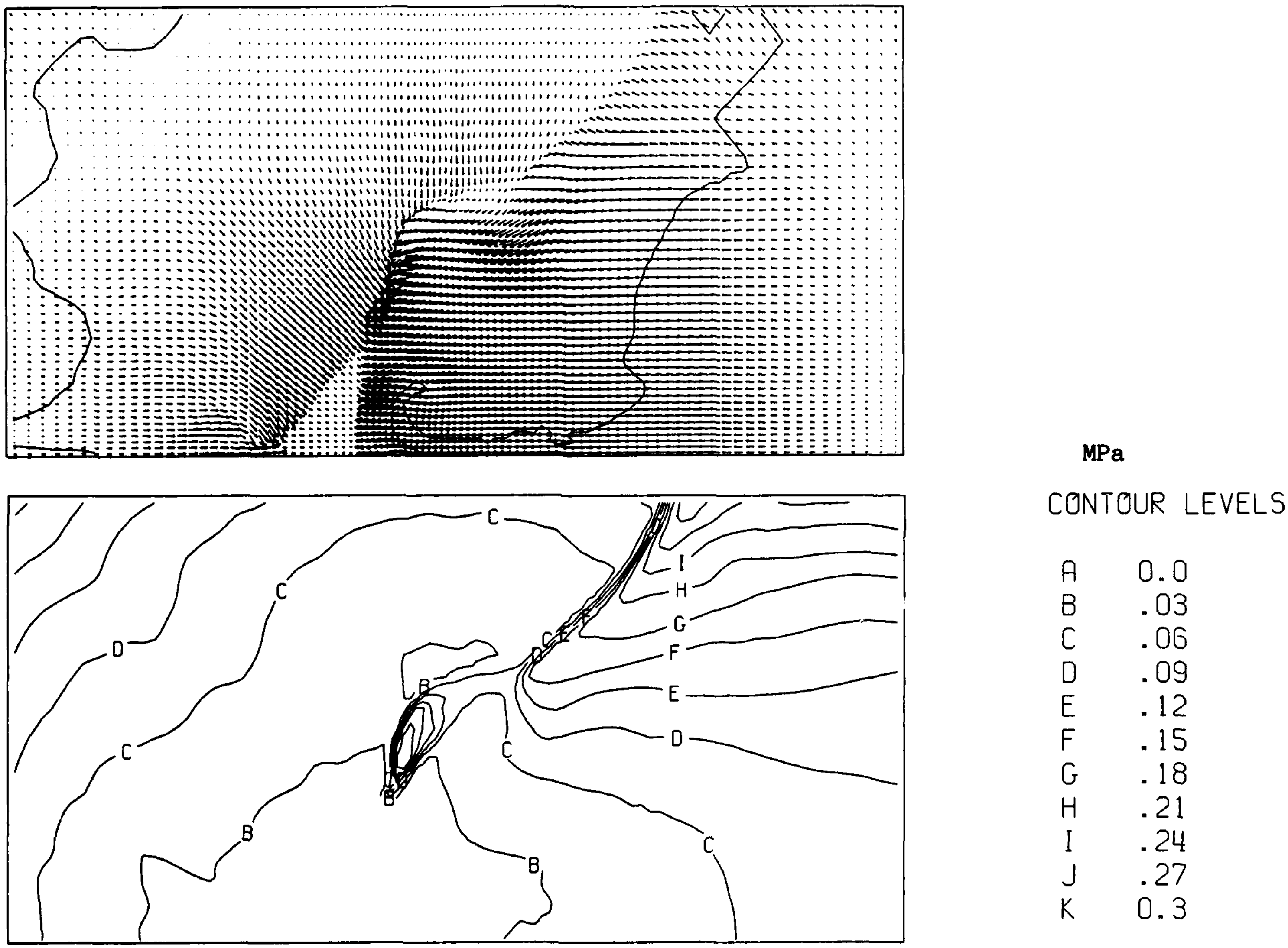

FIGURE 6: VELOCITY VECTOR PLOT AND PRESSURE CONTOURS AT t = 1.35 ms.

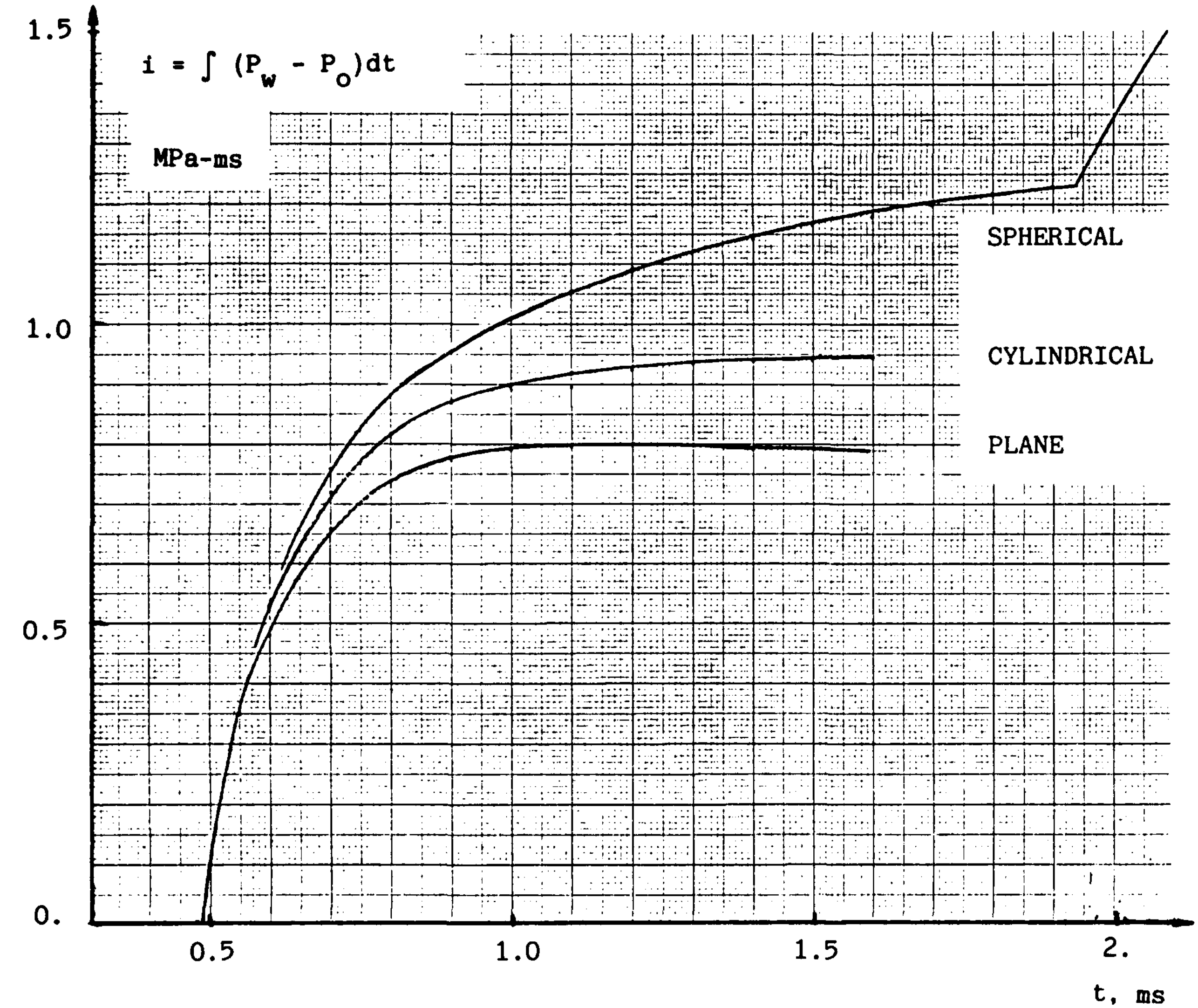

FIGURE 7: THE REFLECTED WAVE IMPULSE VS. TIME

DISPOSAL OF LIQUID PROPELLANT ROCKET MOTORS

LT. COL. MEIR SAVARIEGO (RET.)*

ABSTRACT THE ISRAEL MINISTRY OF DEFENSE CONTRACTED I.E.O.D. ENGINEERING LTD. FOR THE TASK OF THE DISPOSAL OF TENS OF BULLPUP AGM TYPE ROCKET MOTORS. THESE MOTORS CONTAIN FUEL AND OXIDIZER - A HYPERGOLIC LIQUID PROPELLANT SYSTEM. THE PROPOSED AND EXECUTED DISPOSAL METHOD WAS IGNITION OF THE MOTORS. A REMOTE DESERT SITE WAS SELECTED FOR THE DISPOSAL WORK. A BURNING PIT WAS EXCAVATED FOR EACH ROCKET MOTOR. A FIRING CABLE WAS LAID FROM EACH MOTOR TO A REMOTE CENTRAL LOCATION. THE MOTORS WERE EMPLACED AND IMPROVISED ELECTRICAL IGNITERS WERE INSERTED IN THE MOTOR'S IGNITION DEVICE WELL. DURING DISPOSAL, THE MOTORS WERE IGNITED INDIVIDUALLY WITH DELAYS BETWEEN THEM DEPENDING ON THE WIND SPEED AND DIRECTION. DETAILS ARE GIVEN FOR A CASE OF ONE MOTOR WHICH WAS DESTROYED IN PLACE DUE TO ITS HAZARDOUS CONDITION. THE DISPOSAL EFFORT EXTENDED OVER TWO WEEK PERIOD. DETAILS ARE GIVEN FOR THE CASE OF ONE MOTOR WHICH WAS DESTROYED IN PLACE DUE TO HAZARDOUS CONDITION.

BACKGROUND

THE USER OF THE BULLPUP AGM-12E SYSTEM DECIDED, THAT IT WAS NO LONGER AN IN-SERVICE ITEM. IT WAS THEREFORE DECIDED TO DISPOSE OF THE INVENTORY OF THESE ROCKET MOTORS.

I.E.O.D. ENGINEERING LIMITED WAS CONTRACTED TO PROVIDE THE DISPOSAL SERVICES FOR THE DESTRUCTION OF ABOUT 180 OF THESE UNITS.

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MOTOR CHARACTERISTICS

THE AGM-12E ROCKET MOTOR HAS THE FOLLOWING BASIC CHARACTERISTICS:

1. LENGHT	-	156.2 CM
2. DIAMETER	-	44.0 CM
3. TOTAL WEIGHT	-	254.0 KG
4. OXIDIZER	-	I.R.F.N.A
5. OXIDIZER WEIGHT	-	115.0 KG
6. FUEL	-	U.D.M.H
7. FUEL WEIGHT	-	41.0 KG
8. SOLID PROPELLANT	-	DOUBLE BASE
9. SOLID PROPELLANT WEIGHT	-	7.0 KG
10. BURNING TIME	-	2.25 SEC.

DISPOSAL METHODS

THREE METHODS OF DISPOSAL OF SUCH ROCKET MOTORS AS THE ONE USED IN THE BULLPUP SYSTEM WERE CONSIDERED.

A. DRAINING AND NEUTRALIZING THE OXIDIZER BY CAUSTIC SODA AND THEN SIMPLE BURNING OF THE LIQUID FUEL AT A RATE OF 40 LITERS AT A TIME.

B. DESTRUCTION BY EXPLOSIVES. DETONATING A T.N.T. CHARGE PLACED IN CONTACT WITH THE ROCKET MOTOR.

C. IGNITION OF THE ROCKET MOTOR IN A MANNER SIMILAR TO THE CONVENTIONAL FUNCTIONING OF THE PROPELLANT.

THE FIRST METHOD THAT OF DISPOSAL BY NEUTRALIZATION IS THE MOST COSTLY AND TIME CONSUMING. IN ADDITION, IT IS THE MOST HAZARDOUS OF THE THREE METHODS PROPOSED.

WHEN DISPOSING OF ROCKET MOTORS BY EXPLOSIVE DESTRUCTION THE RESULTING DEBRIS IS SPREAD OVER A WIDE AREA. THIS METHOD IS NOT THE MOST DESIRABLE AND SHOULD BE USED ON SPECIAL OCCASIONS WHERE OTHER METHODS ARE NOT PRACTICAL.

IN THE EFFORT DESCRIBED IN THIS PRESENTATION THE THIRD METHOD WAS SELECTED FOR ALL EXCEPT ONE CASE. ONE OF THE ROCKET MOTORS HAD TO BE DISPOSED OF BY EXPLOSION FOR SAFETY REASONS. THIS SPECIAL CASE WILL BE DESCRIBED LATER.

THE DISPOSAL EFFORT

A REMOTE DESERT SITE IN THE SOUTH OF ISRAEL WAS SELECTED FOR THIS WORK SO AS TO BE FAR, ABOUT 30 KILOMETERS FROM POPULATED AREAS. THE DISPOSAL SITE ITSELF WAS PLANNED SO THAT THE PREVAILING WINDS WOULD DRIVE THE PRODUCTS OF THE BURNING AWAY FROM THE DISPOSAL TEAM IN THE CONTROL BUNKER.

THE ROCKET MOTORS WERE DELIVERED TO THE AREA AND WERE TEMPORARILY STORED IN AN ORDERLY MANNER IN THE OPEN AT ABOUT 2 KILOMETERS FROM THE DISPOSAL SITE. THE STORAGE AREA WAS ALSO ISOLATED BY A HILL FROM THE BURNING SITE.

EXCAVATIONS WERE MADE AT THE DISPOSAL SITE TO ACCOMODATE EACH ROCKET MOTOR. TWO SETS OF TWENTY (20) INDIVIDUAL EXCAVATIONS WERE PREPARED , ONE SET FOR EACH DAY OF WORK. EACH EXCAVATION WAS 0.8 METERS WIDE AND SLOPED DOWNWARD AT AN ANGLE OF ABOUT 15 DEGREES FROM THE SURFACE TO A DEPTH OF 1.2 METERS. ADJACENT EXCAVATIONS WERE SEPARATED BY ABOUT TWO METERS.

PRIOR TO THEIR REMOVAL FROM THE STORAGE AREA THE ROCKET MOTORS WERE CHECKED FOR ANY LEAKING OF OXIDIZER OR OF FUEL BY THE USE OF HAND HELD GAS DETECTOR. NO LEAKING PROPELLANT COMPONENTS WERE DETECTED THROUGHOUT THIS DISPOSAL EFFORT.

TWENTY ROCKET MOTORS WERE THEN TRANSPORTED BY A CRANE EQUIPPED TRUCK TO THE DISPOSAL SITE. THIS WAS THE DAILY AMOUNT OF ROCKET MOTORS DISPOSED OF DURING THIS EFFORT. THE MOTORS WERE PLACED WITH ROCKET NOZZLE TOWARDS THE SURFACE SO THAT THE EARTH BURDEN WOULD TAKE THE THRUST OF THE MOTOR.

PRIOR TO THE EMPLACEMENT AND ARMING OF THE MOTORS TO BE DISPOSED OF ON EACH DAY, THE "EMPTY" MOTORS FROM THE PREVIOUS DAY'S WORK WERE CHECKED BY THE GAS DETECTOR FOR REMNANTS OF FUEL OR OXIDIZER. NO HYDRAZINE WAS DETECTED IN ANY OF THE "BURNED-OUT" ROCKET MOTORS. INHIBITED RED FUMING NITRIC ACID WAS DETECTED IN SMALL AMOUNTS.

CONSEQUENTLY, THE "EMPTY" CASES WERE PLACED INTO A TANK CONTAINING WATER AND CAUSTIC SODA WHICH NEUTRALIZED THE OXIDIZER WHICH WAS NOT CONSUMED IN THE BURNING PROCESS.

THE ARMING PROCEDURE WAS AS FOLLOWS:

AS THE IGNITION METHOD WAS ELECTRICAL, TWISTED FIRING WIRES WERE LAID FROM EACH EXCAVATION TO THE CONTROL BUNKER LOCATED THREE HUNDRED AND FIFTY (350) METERS FROM THE EXCAVATIONS. IMPROVISED ELECTRICAL IGNITERS CONSISTING OF AN ELECTRICAL MATCH HEAD AND BLACK POWDER IN A WOODEN DOWEL WERE CONNECTED TO THE SHORTED FIRING LINES. THE FINAL STEP WAS THE INSERTION OF THE IGNITER INTO THE MOTOR'S IGNITION DEVICE WELL. THE SITE WAS THEN EVACUATED BY THE TWO MAN ARMING TEAM WHO RETURNED TO THE CONTROL BUNKER. THE DISPOSAL SITE WAS UNDER SURVEILLANCE BY A CLOSED CIRCUIT TELEVISION SYSTEM WITH A MONITOR LOCATED IN THE CONTROL BUNKER.

AN AMBULANCE AND MEDICALLY TRAINED PERSONNEL WERE ON LOCATION DURING ALL OPERATIONS. THE AMBULANCE WAS LOCATED ON NEARBY HILL WITH EXCELLENT OBSERVATION CAPABILTY OF THE ENTIRE OPERATION.

WIND CONDITIONS WERE CHECKED BY AN ANEMOMETER, PRIOR TO EACH IGNITION TO BE SURE THAT THE DIRECTION AND SPEED WERE SUITABLE FOR CONDUCTING THE OPERATION. WIND SPEEDS OF BETWEEN 4 AND 8 METERS PER SECOND WERE CONSIDERED SATISFACTORY FOR THIS WORK.

AN M-34 BLASTING MACHINE WAS USED TO FIRE THE INDIVIDUAL ROCKET MOTORS VIA THE IMPROVISED IGNITERS. A DELAY OF AT LEAST FOUR (4) MINUTES WAS USED BETWEEN FIRINGS, THERE WERE NO CASES OF PROPAGATION BETWEEN THE ROCKET MOTORS.

A SPECIAL CASE

ONE OF THE AGM-12 ROCKET MOTORS HAD SIGNS OF SEVERE CORROSION IT WAS DECIDED TO DISPOSE OF THIS MOTOR BY PLACING A 30 KG CHARGE OF T.N.T PELLETS ON THE CASING OF THIS UNIT. THE MOTOR WAS THUS DESTROYED BY A DETONATION NO PROPELLANT REMAINS WERE FOUND AFTER THE EXPLOSION.

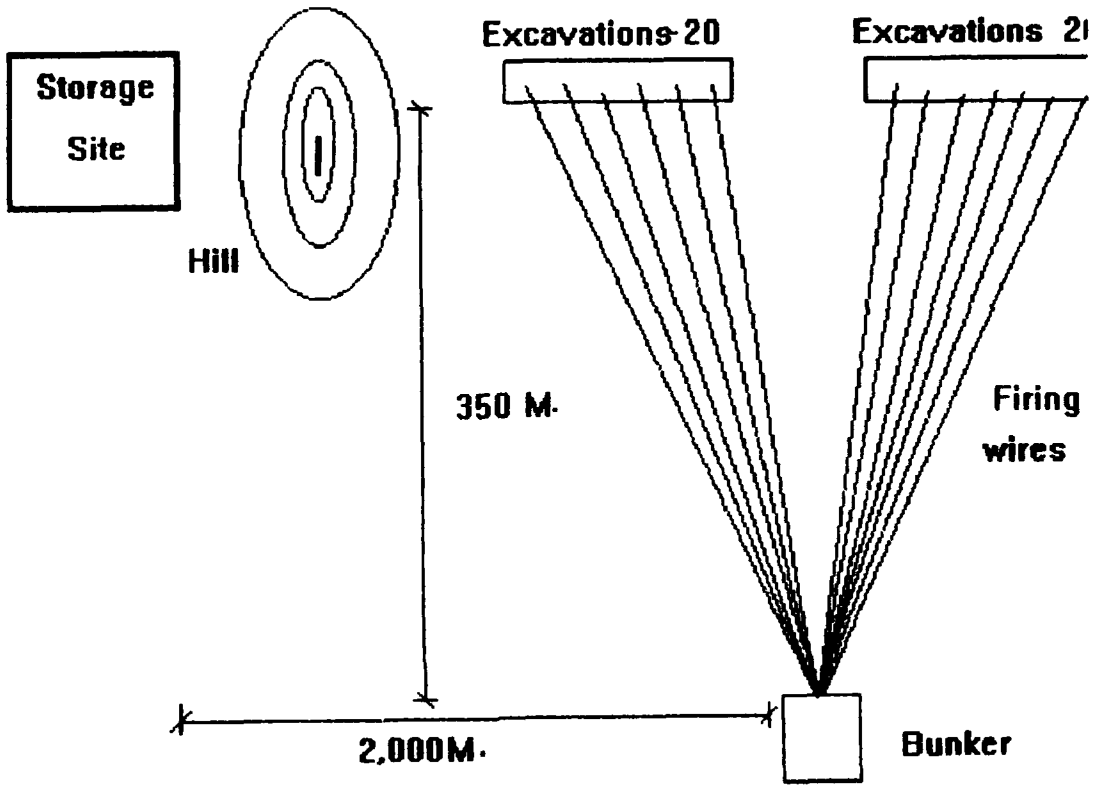
SUMMARY

A TOTAL OF ONE HUNDRED AND EIGHTY (180) BULLPUP AGM-12 ROCKET MOTORS WERE DISPOSED OF IN A SAFE AND EXPEDIENT FASHION.

THE DISPOSAL METHOD SELECTED, IGNITION OF THE PROPELLANT, WAS THE MOST SUITABLE IN TERMS OF COST AND TIME EFFICIENCY. THE GASES GENERATED ARE BASICALLY THE SAME AS THOSE DURING THE ACTUAL USE OF THE ROCKET MOTOR.

THE METHOD USED OF EMPLACING THE MOTOR "HEAD-FIRST" INTO A SLOPING EXCAVATION AND SUBSEQUENTLY IGNITING THE ROCKET MOTOR USING AN IMPROVISED IGNITER WAS FOUND TO BE SATISFACTORY.

IN THE SPECIAL CASE WHERE IT WAS NECESSARY TO DISPOSE OF A CORRODED ROCKET MOTOR BY THE DETONATION METHOD, NO REMAINS WERE DETECTED OF UNREACTED PROPELLANT COMPONENTS.


Storage
Site
Hill
Excavations 20
Excavations 2
350 M.
Firing
wires
2,000M.
Bunker

AEDC CAPABILITY TO PERFORM ENVIRONMENTALLY SAFE DISPOSAL OF SOLID-PROPELLANT ROCKET MOTORS*

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ABSTRACT

The Department of Defense (DoD) has in its storage and operational arsenals an increasing number of large solid-propellant rocket motors (SRM's). There is a need to provide an environmentally acceptable and safe method for the demilitarization, elimination, destruction, or disposal of these SRM's. The Environmental Protection Agency (EPA) has requested those involved to identify methods of disposal, other than Open Burning/Open Detonation (OB/OD), which have less pollution. Arnold Engineering Development Center (AEDC) has been in the altitude, environmental chamber, test mode for over 30 years and has analyzed and treated the environmental issues to the satisfaction of local, state, and federal environmental agencies. AEDC conducted a study of various concepts applicable to the environmentally safe disposal of SRM's based on AEDC altitude rocket testing expertise.

The study looked at the technical feasibility of several proposed concepts for SRM disposal at AEDC. The adaptation of existing facilities for SRM disposal was considered as well as new facilities.

INTRODUCTION

The Environmental Protection Agency (EPA) has advised all the Department of Defense (DOD) facilities that the Resource Conservation and Recovery Act (RCRA) Subpart X was not intended to allow continued operation of Open Burning/Open Detonation (OB/OD) without valid justification.[1] Minimum technology standards are not applicable for the justification, and the facilities must use environmental performance standards. Since disposal of the SRM's is a joint service issue, the Joint Ordnance Commander's Group (JOCG) is exploring alternate disposal techniques which control the release of toxins and contaminants to the environment. AEDC is a member of the JOCG Munitions Demilitarization Subgroup addressing this issue, and has conducted a feasibility study of the possibility of using the test firing modus operandi as an environmentally safe method of disposal. The primary objective of this paper is to describe the capability of AEDC, using test firing techniques, to dispose of SRM's in an environmentally safe manner.

*The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command. Work and analysis for this research were done by personnel of Sverdrup Technology, Inc., AEDC Group, operating contractor for the AEDC propulsion test facilities. Further reproduction is authorized to satisfy needs of the U. S. Government.

Technical Feasibility

Constraining Assumptions

When AEDC began to study the concept of Large Solid Rocket Motor (SRM) disposal using test cell technology, the disposal mission was very poorly defined. The disposal need consisted of two main components: those motors retired from service due to age and those retired due to treaty requirements. A low-cost, low-technology, high-throughput disposal facility was the fundamental basis for the concepts explored by this study. Because of the preliminary nature of the disposal mission when this study began, the team started by identifying and evaluating a set of constraining assumptions. Each of these assumptions will be discussed below.

At the time, AEDC identified at least 2,000 motors which were slated for disposal over a ten-year period. These motors were from current inventories of Poseidon (C3), Trident (C4 and D5), Peacekeeper, Minuteman II and III, and Small ICBM (SICBM). The explosive hazard classifications of these motors are Class/Division 1.3 and Class/Division 1.1. The first assumption that was the emphasis of the disposal effort would be on Class/Division 1.1 motors because of the alternative reclamation technology efforts under study for the Class/Division 1.3 HTPB propellants. Further, no motor larger than 83,000 lbm of 1.1 propellant or 100,000 lbm of Class/Division 1.3 propellant would be disposed of. These limits match the current explosive siting limits for Large Rocket Test Facility J-6.[2]

Disposing of Class/Division 1.1 motors presents a greater technical challenge than does the Class/Division 1.3 motors. Since the population of these motors includes potentially defective propellant grains, the risk of detonation is higher than it is for normal test operations. AEDC assumed a technology demonstration effort would reduce the facility risk to the extent that a detonation during motor burn would be an extremely unlikely but potentially catastrophic event.

To keep the disposal operations moving smoothly, and for facility safety, the disposal mission is constrained to whole motors only. Motor fragments, propellant segments, and dissected motors were excluded from this study due to issues associated with logistics and unpredictabilities of results.

The environmental assessment and license acquisition was perceived to be a very unknown obstacle to any disposal operations throughout the solid-propellant rocket community. Since most of the parties active in the manufacturing are located in the western states, we were very interested in the attitude of the regulators for the Tennessee region. After discussions with state representatives, this study assumed that obtaining the necessary permits is possible.

The assumptions necessary for identifying motor storage and logistics requirements presented some conflicting points of view. Inspection and verification requirements associated with START treaty demilitarization efforts were not defined, but could be perceived as conflicting with the security requirements of the testing mission at AEDC. The complete implications of demilitarization treaty requirements remains an open issue, but the siting of a disposal location at AEDC is assumed possible while protecting the testing mission security requirements.

Disposal Concepts

Within the constraining assumptions discussed above, three general disposal concepts were considered: using existing facilities without major modifications; using existing facilities with major modifications; and constructing new facilities at AEDC. Twelve possibilities came out of an industry survey, which were then evaluated against factors such as cost, safety, environmental controls, and impact to the testing mission. This evaluation process resulted in three concepts that provided the most favorable approaches, considering technical, economic, and political factors. The three concepts which were carried through the detailed cost estimating phase of the study were: use of the J-6 facility (Fig. 1); construction of an additional burn chamber to J-6 (Fig. 2); and a standalone steam ejector and scrubber cell (Fig. 3). Please note that J-6 is the only existing AEDC facility that is explosives sited to test 83,000 lbm of Class/Division 1.1 and 100,000 lbm of Class/Division 1.3.

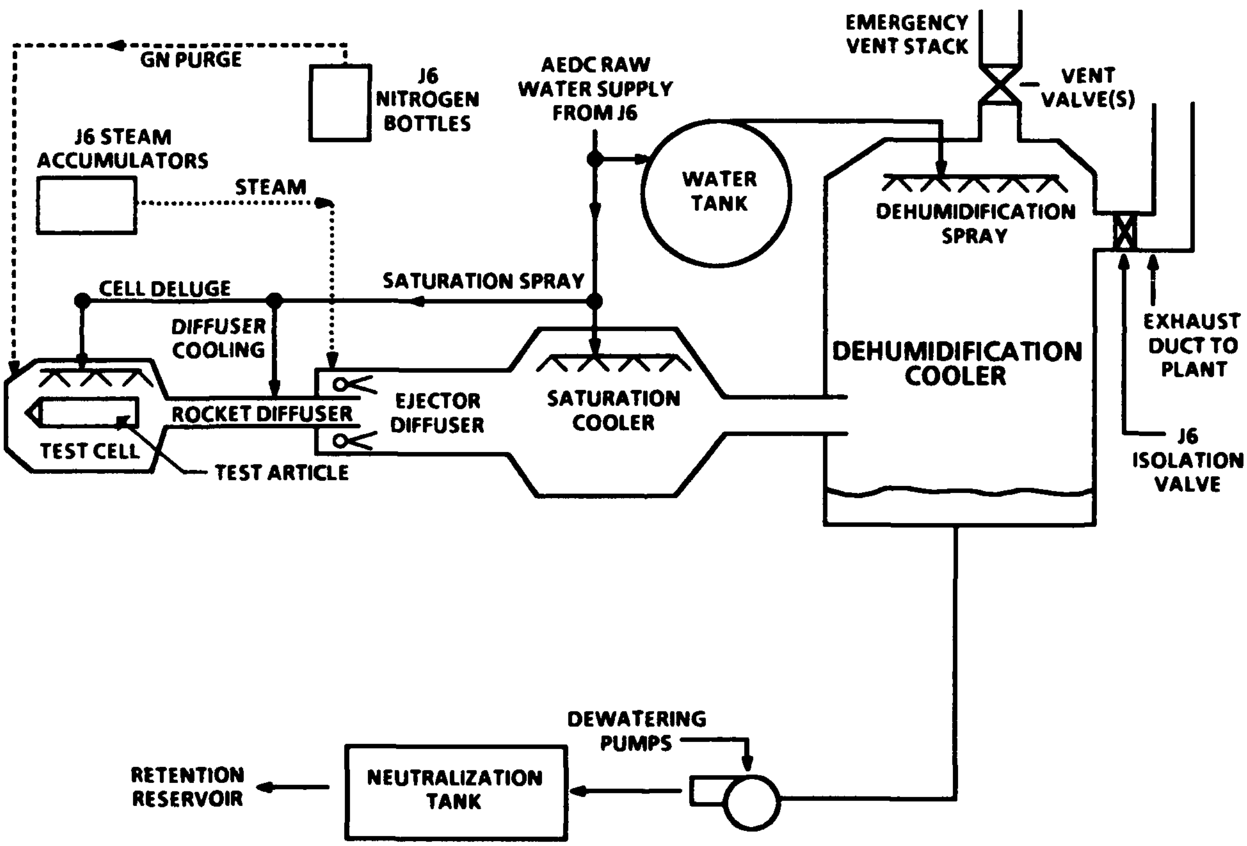

Fig. 1. J-6 operational schematic.

The use of the J-6 facility would minimize construction of new facilities. This concept would use available J-6 plant facility and require some modifications of the test cell itself to remove or protect unneeded high-value equipment such as the thrust measurement system and to improve throughput efficiency. Addition of a water neutralization step in the J-6 dewatering system would be required with the quantities of propellant exhausts being considered here. The use of J-6 would impact

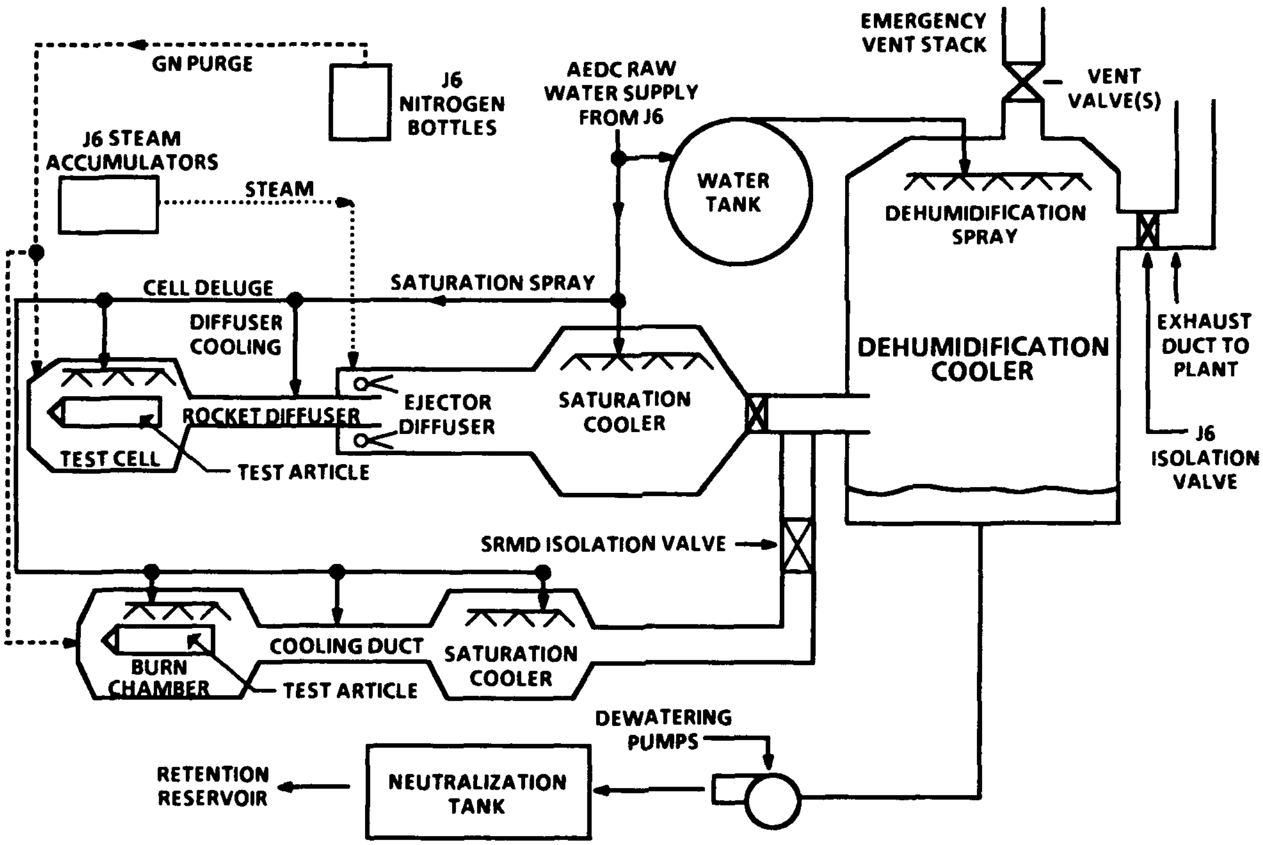

Fig. 2. J-6 leg operational schematic.

scheduled J-6 and Engine Test Facility (ETF) Test and Evaluation (T&E) programs, and also require use of the ETF exhauster facility.

Addition of a separate burn chamber to the J-6 ducting provides several advantages while requiring higher initial costs. First, the burn chamber could be located to provide the necessary distance from the test and evaluation cell to meet intraline distance requirements and reduce impacts to its programs. Second, higher initial construction costs can be offset by designing the disposal cell for maximum production rate efficiency.

A standalone, steam ejector-pumped cell with scrubbing will provide a high level of efficiency and minimize all the interfaces with the J-6 facility. By operating totally separate from the ETF exhauster plant, impacts to the T&E work would be centered only on the coordination of steam, water, and gaseous nitrogen (GN_2) from the J-6 facility. Because of the steam ejector equipment, costs to construct this facility would be the highest of the three approaches.

ENVIRONMENTAL RESTRICTIONS

The large SRM disposal activity at AEDC will be characterized as a "Hazardous Waste Disposal" activity. It will not be classified as an SRM "testing" or "reclamation" activity. The disposal activity will be governed by Subpart X "Miscellaneous

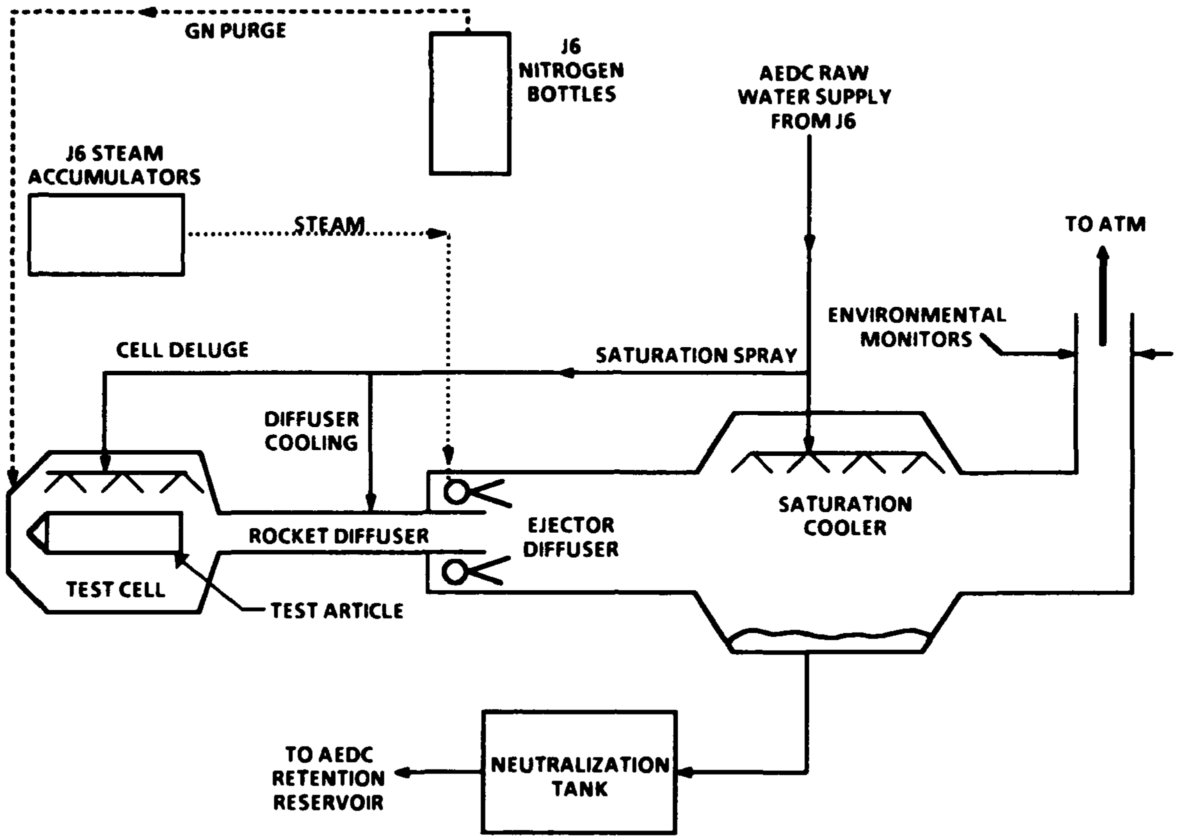

Fig. 3. Ejector to atmosphere operational schematic.

Units" regulations of 40 CFR 264 under the Resources Conservation and Recovery Act. This Subpart X regulation provides for the protection of human health and the environment. It includes, but is not limited to, the prevention of any releases that may have adverse effects on human health or the environment due to: migration of waste constituents in the ground water or subsurface environment; migration of waste constituents in the surface water, or wetlands or on the soil surface; or migration of waste constituents in the air.

A miscellaneous (disposal) unit permit must also contain design and operating requirements, detection and monitoring requirements, and plans for responses to release of hazardous waste or hazardous constituents from the unit to ensure protection as specified in Subpart X.

The SRM's for disposal will include both hazard Class/Division 1.1 and 1.3 propellants which contain various chemical compositions. The technology utilized at AEDC is an environmentally safe and readily available alternative to OB/OD. Information on the composition of various Class/Division 1.1 and 1.3 SRM's that are in the disposal inventory was assessed. Various SRM propellant composition and operational characteristics were input using the NASA SP-273 computer code to predict the SRM's exhaust gas products. A summary of the results is shown in Table 1. The range of both mole fractions and weight fractions is given for the exhaust constituents.

Table 1. Typical SRM Propellant Exhaust Product Composition and Proportion Range

EXHAUST PRODUCTS	MOLE FRACTION RANGE	GAS	LIQUID	SOLID	WEIGHT FRACTION RANGE
Carbon Monoxide (CO)	0.18 — 0.19	X			0.16 — 0.17
Hydrogen Choride (HCl)	0.11 — 0.16	X			0.13 — 0.19
Aluminum Oxide (Al_2O_3)	0.09 — 0.09			X	0.29 — 0.29
Hydrogen (H_2)	0.23 — 0.27	X			0.01 — 0.01
Aluminum Chloride (AlCl)	0.02 — 0.05			X	0.04 — 0.10
Chloride Radical (CL)	0.03 — 0.04	X			0.02 — 0.03
Hydrogen Radical (H)	0.08 — 0.09	X			0.002 — 0.002
Water (H_2O)	0.04 — 0.07		X		0.02 — 0.04
Nitrogen (N_2)	0.07 — 0.07	X			0.06 — 0.06
Hydroxide (OH)	0.006 — 0.010	X			0.003 — 0.005
Hydrogen Cyanide (HCN)	4E-7 — 1E-6	X			3E-1 — 8E-7
Carbon Dioxide (CO_2)	0.004 — 0.007	X			0.006 — 0.009
Nitric Oxide (NO)	3E-4 — 7E-4	X			6E-7 — 2E-4
Nitrogen Dioxide (NO_2)	<5E-7 — <5E-7	X			7E-7 — 7E-7
Aluminum (Al)	0.001 — 0.003			X	8E-4 — 2E-2
Aluminum Nitride (AlN)	<5E-7 — <5E-7			X	6E-7 — 6E-7
Dialuminum Oxide (Al_2O)	3E-4 — 2E-3			X	6E-4 — 4E-3

By-Products To Be Disposed

The SRM exhaust products shown in Table 1 contain all three states of matter (gas, liquid, and solid). The majority of the exhaust products are gases and one of the predominant ones (13%) is hydrogen chloride (HCl), which, when mixed with the spray water, becomes a hydrochloric acid solution. Water is the main liquid product. The predominant solid residue is aluminum oxide, which comprises about 30 percent of the total exhaust product.

An exhaust gas management system consisting of steam ejectors, spray water scrubbers, exhaust ducting, exhausters, and exhaust stacks all combine to condition the exhaust products to a state where it is acceptable to the environment. The functions of the exhaust gas management system are to: cool the exhaust products from approximately 6,000°F to around 100°F; remove the solid aluminum oxide particles and the water soluble products such as hydrogen chloride; compress the exhaust gas before it is discharged to the atmosphere; and abate the fire/explosion hazard in the ducting because of the hydrogen and carbon monoxide in the exhaust products. The scrubbing of the exhaust gas by direct water sprays, and its discharge

to atmosphere are the main ingredients which contribute to an environmentally safe disposal system.

Environmental Impact Analysis

The preparation of an environmental assessment and a Finding of No Significant Impact (FONSI) will help fulfill the requirements of the National Environmental Policy Act (NEPA). If the environmental assessment reveals that the impact will be significant, then it will be necessary to prepare an Environmental Impact Statement (EIS) instead of a FONSI. The EIS, a much more detailed analysis, will take almost twice as long to complete as the FONSI at considerably more cost.

Environmental Permits

Members of the Tennessee Department of Environment and Conservation (TDEC) were briefed on the environmental aspects of the controlled disposal concept. The preliminary response from the TDEC concerning the possibility of siting a large rocket disposal facility at AEDC was very favorable. A letter was received from the TDEC in October 1991 which stated that "to date, no environmental issue has been recognized that would threaten the project." The Subpart X permit can be issued as an amendment to AEDC's existing Part-B RCRA permit for storage. TDEC also stated that for converting a test unit to a nonhazardous waste unit, full closure requirements will apply. AEDC must establish pre-disposal operation contamination levels, i. e., existing levels resulting from testing operations, to be used as a baseline to compare against closure cleanup standards.

Additionally, both air and water discharge permits will be required for the disposal operations. TDEC stated in their letter that a PSD (prevention of signification deterioration) review will be required prior to issuance of an air permit for the disposal operation. The water discharge permit for the scrubber water will be meshed into the current National Pollutant Discharge Elimination System (NPDES) permit. AEDC's construction landfill permit will have to be modified to identify Al_2O_3 sludge as a waste for disposal.

Source Monitoring

The air permit for the disposal operation will likely require source monitoring for particular exhaust products. The permit-required monitoring would include specifications on sampling, measurements, and sensitivity of analysis. TDEC feels that the high-flow, short-duration emission from a rocket motor firing is not suitable for the application of electro-optical monitoring equipment which is normally set up for continuous monitoring of long-duration emissions. Therefore, sampling and laboratory analysis of exhaust products would be a preferred method of emission monitoring.

CONCLUSIONS

The use of AEDC testing expertise and existing facilities is a sound, technically feasible solution for the disposal operations in an environmentally acceptable manner. The residual material in the exhaust gas can be handled and returned to the base ecological system in an occupationally and environmentally safe manner. The

State TDEC's preliminary response to the proposed concepts of disposal has been very encouraging.

REFERENCES

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2. Mohyuddin, Z., Cyran, F. B., and Le, T. V., "Potential Applications of Rocket Test Exhaust Scrubber Techniques to Solid Rocket Demilitarization At Arnold Engineering Development Center," Paper presented at JANNAF Safety and Environmental Subcommittee Meeting, August 1992, Monterey, CA.

DEGRADABLE AND HYDROLYZABLE BINDER EXPLOSIVES

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ABSTRACT

High explosives cast in military hardware are generally prepared to meet the demands of rough handling, as well as long-term storage. At some point, however, if the ordnance items that contain them are not detonated as intended, the explosives lose their effectiveness and reliability. Excessive aging, deterioration, or some other unanticipated event will require their safe disposal.

Air pollution abatement and environmental control regulations have now imposed constraints on methods of disposal and demilitarization of unserviceable ordnance explosives. An attractive alternative to continued open burning and demolition would be the development of a cast explosive whose main constituents could be degraded and recycled into reusable explosive solids and liquid by-products which are environmentally non-hazardous.

Past research and technology work at the Naval Air Warfare Center Weapons Division, China Lake, Calif., has culminated in the successful development of a castable plastic-bonded explosive composition that has the following desirable characteristics: (1) it is water degradable and leaves no toxic products behind; (2) it contains a binder which hydrolyzes but does not form a highly viscous gel; (3) it contains a binder which does not degrade in the presence of water alone; and (4) it produces an acceptable energy output level as a main charge explosive.

This finalized explosive composition, PBXC-125, consists of a simple two-component polyurethane binder system with 82% RDX. On degrading in a dilute ammonia solution, the polymerized binder breaks down to a diol and lysine, respectively—two non-polluting and harmless by-products. The main solids component (RDX) can be filtered, washed, dried, and then recycled, if necessary. The potential for this explosive's safe and rapid demilitarization was also demonstrated in a high-pressure water washout facility. Under the action of a high-pressure water jet, the cast explosive fill in a simulated warhead round was effectively removed in only a few seconds. Additional associated safety and sensitivity tests, performance tests, and thermal cookoff data will be described.

INTRODUCTION

Military ordnance items containing high explosives are generally designed to withstand the rigors of rough handling and long-term storage, and to meet high reliability standards. However, if these ordnance items are not detonated as intended, they lose their effectiveness and reliability. Excessive aging, deterioration, or some other unanticipated event will then mandate that they be demilitarized and disposed of in an efficient, safe, and non-polluting manner.

Current air pollution abatement and environmental control regulations have imposed constraints on past methods of disposal and demilitarization of unserviceable ordnance explosives (References 1-3). An attractive alternative to continued open burning and demolition would be the development of a cast explosive whose main constituents could eventually be degraded and recycled into reusable explosive solids and liquid by-products which are environmentally non-hazardous. For several years the Naval Air Warfare Center Weapons Division, China Lake,

Calif., has performed research and technology work concerned with the development of a castable plastic-bonded explosive composition that has the following characteristics:

1. Is water degradable at a good rate and produces no toxic degradation products.
2. Contains a binder that hydrolyzes and forms no high viscosity gels.
3. Contains a binder that does not degrade in the presence of water alone.
4 Contains an adequate explosive solids and energy output level.

This paper describes the efforts that went into accomplishing these objectives.

APPROACH

Separation and recovery of ingredients from conventional high explosives are never simple and become particularly complex for plastic-bonded explosives. Such compositions contain a polymeric binder that has been reacted with a curativė (cross-linking agent) to provide the mechanical strength necessary to maintain the explosive as a single coherent mass. To isolate the ingredients, the cross-linked polymer must be degraded to avoid the formation of viscous gels, which would inhibit the rate of degradation of the explosive. Although not recognized as being recyclable, the degraded polymeric binder should nevertheless yield only chemical species that are relatively innocuous. Excluding physical demilling operations, presently employed polymers for plastic-bonded explosives are not readily degraded.

Our approach, therefore, was to formulate exploratory, castable plastic-bonded explosives that would lend themselves to chemical degradation and separation of the binder from the solids fill. Moreover, to become competitive with existing Navy-approved high explosive compositions, our formulations had to pass the mandatory tests required by the Navy manual for interim qualification of explosives (Reference 4).

Emphasis was placed on using commercially available binder ingredients. Experience gained from working with solid propellant formulations was applied. Polyurethane binders that would undergo hydrolysis and breakdown by very dilute ammonia or acid solutions, but not by water (or moisture) alone, were initially selected. With HMX or RDX comprising the chief solids loading, plasticizers were added as needed to aid processing and casting. Problem areas in mixing and processing, curing, physical properties, explosive sensitivity, component compatibility, and thermal stability were addressed as they occurred.

The successful development of an explosive suitable for Navy qualification as a main charge explosive, but also environmentally safer, became a goal of this program.

BINDER STUDIES AND EXPLOSIVES FORMULATIONS

POLYURETHANES

Polyester and polyether diols readily yield processible formulations that cure with isocyanates to provide strong, flexible, elastomeric composite propellants and explosives. In view of the demonstrated compatibility and the availability of a variety of polyols and isocyanates, the polyurethane/isocyanate system was selected as the degradable binder to be used in the effort described herein.

RDX had demonstrated excellent compatibility with several polyurethanes in cast-cured explosives, and, at the time of this study, it was abundantly available in various classes. HMX, during this period, was reserved for other programs and was, thus, in limited supply.

Preliminary binder studies resulted in the selection of the first two candidates to be used in RDX formulations. The two candidates chosen were a hydroxyl-terminated polyester diol with a PEG adipate backbone (D22-45) and a hydroxyl-terminated polyether diol (L-35).

The high level of ether groups in D22-45 imparts flexibility and enhances the hydrophilic nature of the binder. The polyester also contributes to good processing and rheological properties. The urethanes formed from these polyester diols are capable of hydrolysis and degrade more readily than the polyether polyurethanes. Polyether diols such as L-35 are widely used as binders because of their excellent processing characteristics and their ability to impart elastomeric properties to cured compositions.

Since commercially prepared polyesters are not easily degraded, a curative that produces a urethane linkage capable of ammonolysis or hydrolysis was selected. In this case, it was LDIM. When cured with LDIM, urethane linkage degradation was found to be rapid and complete in dilute acid or ammonium hydroxide. However, when a hydrocarbon diisocyanate curative such as Hylene W was used, the binder showed little or no degradation after several weeks.

Various binder ingredients and combinations were tried in attempts to obtain the most suitable degradation characteristics. RDX fillers were added to the more promising binder formulations. Initial explosive formulations were then characterized as thoroughly as possible. Some of them are shown in the tables that follow.

EXPLOSIVE FORMULATIONS

Processing and mechanical properties were characterized, and minor refinements were made in the composition using the D22-45 polyester binder with the L-35 polyether diol. To aid in processing, as well as improving the aqueous ammonia degradation rate, triacetin was used as a plasticizer. The amount of triacetin ranged from 15 to 20% of binder. The RDX particle size distribution was revised to include some Class 2 size to improve rheology. Generally, the compositions were stable and exhibited no voids, gassing, or swelling under 60°C cure. Curing was completed in two days and yielded flexible compositions that were easily degraded by dilute aqueous ammonia and hydrochloric acid. Two early formulations, SBX-21 and SBX-23, are shown in Table 1.

TABLE 1. Formulations SBX-21 and SBX-23.

Ingredient	Weight %	
	SBX-21	SBX-23
Binder[a]		
D22-45	6.89	5.51
L-35	6.73	8.11
LDIM	1.68	1.68
Triacetin	2.70	2.70
ϕ_3Bi (added)	(0.05)	(0.05)
RDX		
Class 1	15	15
Class 2	22	22
Class 3	15	15
Class 4	30	10
	------------	------------
	100	100
[a] NCO/OH equiv. ratio	1.10	1.10
L-35/D22-45 equiv. ratio	50/50	60/40

Binder-explosive breakdown occurs quite rapidly in dilute aqueous ammonia (5-7%), with the RDX settling out within 24 hours following submersion. This phenomenon is vividly demonstrated in Figures 1 through 4 (the explosive sample in this case is SBX-21). The solid precipitate (RDX) was easily filtered and separated from the clear liquid.

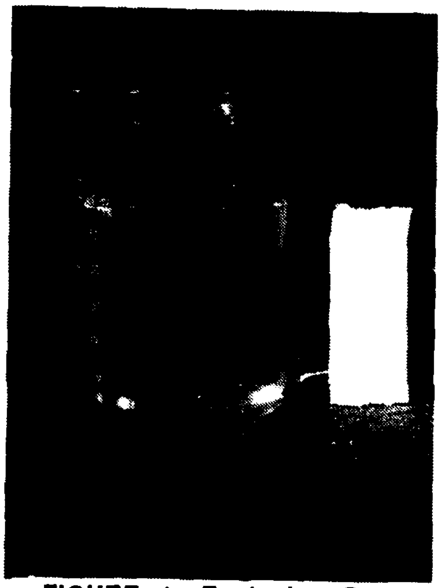

FIGURE 1. Explosive Sample Before Immersion in Dilute Aqueous Ammonia.

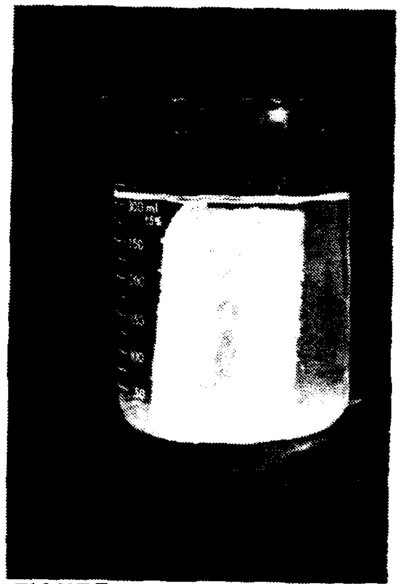

FIGURE 2. Explosive Sample After a Few Minutes Immersion.

FIGURE 3. Explosive Sample After 1 Hour Immersion.

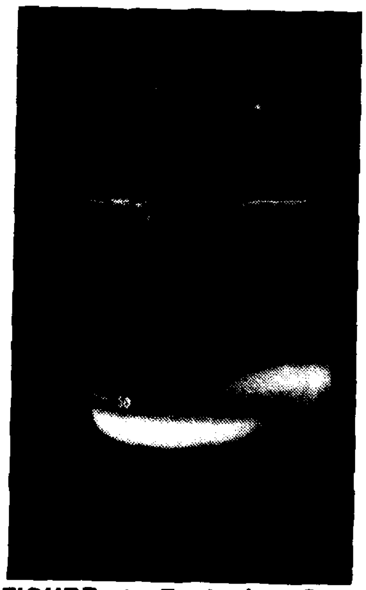

FIGURE 4. Explosive Sample After One Day Immersion.

Because of the irregular nature of the RDX particles and the requirement to maintain a coarse RDX distribution to facilitate its recovery and recycling, the elongation values could not be improved. Binder NCO/OH and L-35/D22-45 equivalence ratios were varied, but no improvement in elongation was obtained. Further attempts to improve the mechanical properties met with little success because of the absence of a suitable bonding mechanism for the coarse RDX fillers at the 82% solids level. Several of the SBX formulations are discussed.

Degradable Binder Explosive SBX-29

Formulation SBX-29 was prepared in a larger 3,000-gram batch size for additional data. Its composition and other properties are shown in Table 2.

TABLE 2. SBX-29 Composition and Properties.

Ingredient	Weight %
Binder	
D22-45	5.05
L-35	9.38
LDIM	1.77
Triacetin	1.80
ϕ_3Bi (added)	(0.05)
(NCO/OH equiv. ratio = 1.10; L-35/D22-45 equiv. ratio = 65/35)	
RDX	
Class 1	
Class 2	82.00
Class 3	
Class 4	
Mechanical Properties	
Tensile strength, kPa (psi)	296 (43)
Elongation at max. stress, %	7
Elongation at rupture, %	9
Modulus, kPa (psi)	5937 (861)
Hazard Properties	
Impact sensitivity	28 cm (RDX = 14 cm)
Friction sensitivity	6/10 no fire at 4.448 kN (1,000 lb)
Electrostatic sensitivity	10/10 no fire at 0.25 J
Thermal Properties	
DTA	Onset of major exotherm, 190°C
TGA	Normal for RDX compositions
Physical Properties	
Shore A hardness	44
Measured density, g/cm^3	1.539
End-of-mix viscosity (60°C), kPa-s	1.35

From this 3,000-gram mix of SBX-29, three units were cast for slow cookoff tests, in accordance with NAVORD OD 4481 (Reference 4). These tests are designed to determine the relative safety of the explosive material as it undergoes self-heating under varied conditions. For this type of tests, each sample is placed in an oven at a set temperature until the sample destroys itself (cooks off). For the purpose of this study, each sample consisted of a one-pint container instrumented with thermocouples and then filled with approximately 700 grams of the explosive.

During these tests, two samples, which were subjected to 130° and 140°C, liquefied and flowed away from the center-embedded thermocouple after the first exotherm peak had passed (at 28 hours and 13 hours, respectively). The third sample reacted normally by deflagrating within 7.5 hours at 200°C.

A DTA pattern for SBX-29 is provided in Figure 5. The decision reached was that SBX-29 *not* be interim qualified in its present form because of excessive self-heating and loss of physical properties on relatively short-term heating.

An extrapolation of the thermal analysis data predicted that, for a 2,000-pound bomb, liquefaction (or other binder degradation) would occur within 500 days at about 65°C. Since NAVORD OD 4481 requires a minimum of 85°C (for a 2,000-pound bomb to self-heat to reaction in 500 days), SBX-29 would not meet this requirement for interim qualification.

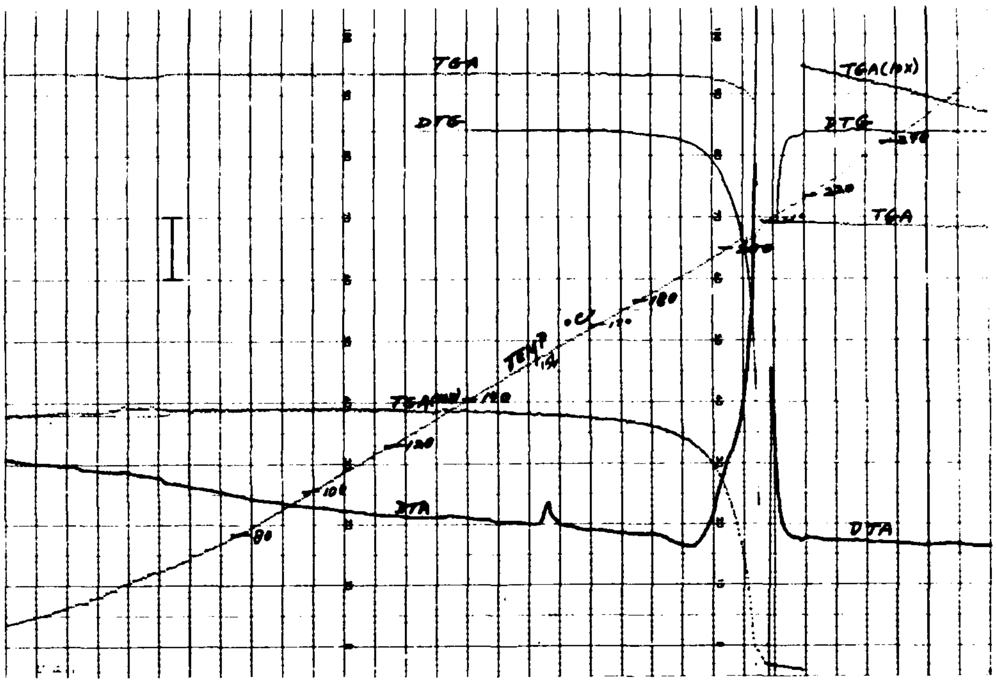

FIGURE 5. Thermal Patterns of SBX-29 at Heating Rate of 3°C/min. (Sample wt.: 26.40 mg; Run No. 8-12-1.

Degradable Binder Explosive SBX-32

Since the plasticizer, triacetin, used in the earlier SBX formulations and in SBX-29 was thought to be the cause of the low-temperature binder degradation reactions, it was dropped from further consideration. No detrimental effects were noticed on processing or cure. The new formulation, SBX-32, is shown in Table 3 with some of its properties.

In addition to DTA/TGA tests, two differently designed slow cookoff experiments were run with SBX-32. The explosive was cast directly into 2-inch by 8.5-inch-high heavy-walled aluminum tubes and was cured. Each tube was fitted with electric heaters controlled by a recorder-controller (Reference 5). The slow isothermal cookoff runs were held at 123° and 139°C, respectively, continuing until explosive liquefaction and foaming occurred. The final results of these slow cookoff runs are shown in Figures 6 and 7.

TABLE 3. SBX-32 Composition and Properties.

Ingredient	Weight %
Binder	
D22-45	5.61
L-35	10.42
LDIM	1.97
ϕ_3Bi (added)	(0.05)
(NCO/OH equiv. ratio = 1.0; L-35/D22-45 equiv. ratio = 65/35)	
RDX	
Class 1	
Class 2	82.00
Class 3	
Class 4	
Mechanical Properties	
Tensile strength, kPa (psi)	565 (82)
Elongation at max. stress, %	6
Elongation at rupture, %	7
Modulus, kPa (psi)	18,283 (2,652)
Hazard Properties	
Impact sensitivity	24 cm (RDX = 14 cm)
Friction sensitivity	6/10 no fire at 4.448 kN (1,000 lb)
Electrostatic sensitivity	10/10 no fire at 0.25 J
Physical Properties	
Shore A hardness	~55
Measured density, g/cm^3	1.583
End-of-mix viscosity (60°C), kPa-s	1.10

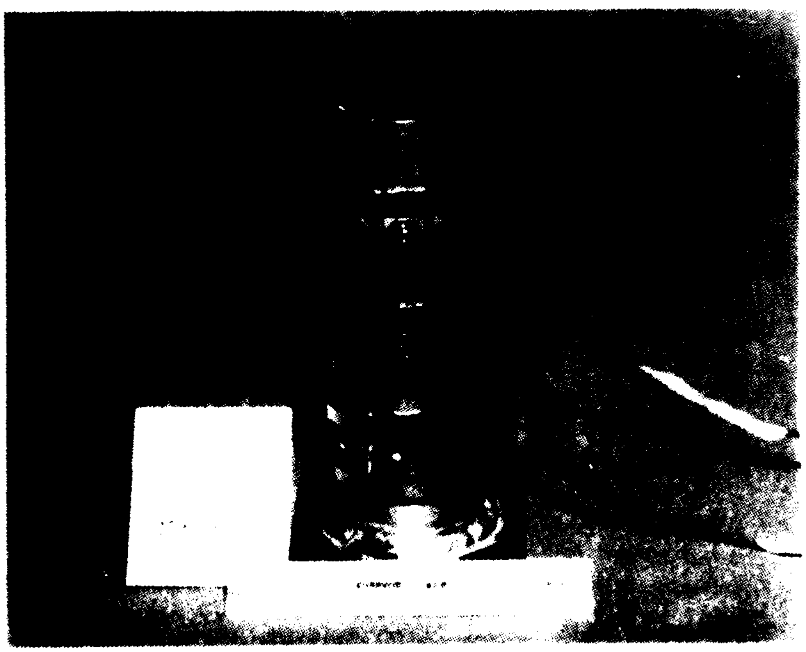

FIGURE 6. Results From First Slow Cookoff Run of SBX-32. Heating bands shown wrapped around circumference.

FIGURE 7. Results From Second Slow Cookoff Run of SBX-32.

The time to reaction of SBX-32 at 139°C agrees well with the data reported earlier for SBX-29, after allowing for the cookoff sample size difference. With this qualitative agreement, the earlier estimate of a low characteristic "critical" temperature for thermal cookoff should stand. SBX-32 was then also dropped from further consideration.

DEVELOPMENT OF CANDIDATE EXPLOSIVE SBX-34

In an effort to further improve the thermal or cookoff behavior of a basic 82% RDX composition such as SBX-32, a simplified binder was adopted. Formrez YA 23-4, an adipate polyester with 79% polyethylene glycol content and a hydroxyl functionality of 2.33 (Witco Chemical Corp.) was chosen. This change would allow the elimination of the polyether diol L-35 from the binder, thus increasing the rate of degradation by ammonia-water.

One further step was taken. A finer RDX particle size in the solids blend was introduced in order to maintain adequate processing characteristics. This change resulted in formulation SBX-34. The end-of-mix viscosity was greatly improved over that of SBX-33. The composition and properties of SBX-33 and SBX-34 are shown in Table 4.

SBX-34 SELF-HEATING SLOW COOKOFF TESTS

SBX-34 was prepared in a 3,000-gram batch and cast into two heavy-walled aluminum tubes with approximately 260 grams of explosive in each. The tubes were then converted into slow cookoff vertical ovens, as for SBX-32, and heated. The results of the SBX-34 self-heating, slow cookoff tests are shown in Table 5.

TABLE 4. Degradable Binder Explosives.

Ingredient	Weight %	
	SBX-33	SBX-34
Binder		
YA 23-4	16.56	16.56
LDIM	1.44	1.44
ϕ_3Bi (added)	(0.05)	(0.05)
(NCO/OH equiv. ratio = 1.2)		
RDX		
Class 1	15	6.56
Class 2	22	—
Class 3	35	14.76
Class 4	10	38.54
Class 5	—	22.14
Mechanical Properties		
Tensile strength, kPa (psi)	614 (89)	552 (80)
Elongation at max. stress, %	3	3
Elongation at rupture, %	28	47
Modulus, kPa (psi)	28,159 (4,084)	27,187 (3,943)
Hazard Properties		
Impact sensitivity, cm	25	23
Friction sensitivity, kN (lb)	3,200 (724)	4,057 (912)
Electrostatic sensitivity, 0.25 J	10/10 no fire	10/10 no fire
VTS, mL/g/48hrs		0.03 (100°C) 0.75 (120°C)
Physical Properties		
Shore A hardness	66	63
Measured density, g/cm^3	1,538	1,602
End-of-mix viscosity (55°C), kPa-s	2.5	1.2

TABLE 5. SBX-34 Slow Cookoff Tests Results.

Test No.	Oven Control Setting, °C	Observations
SCO-338	145	Explosive began foaming after 17.5 hours but no cookoff occurred. Test terminated after 19 hours.
SCO-339	165	Large 218-gram portion of explosive exuded out of oven during heating. Remainder cooked off (no detonation) in 4.5 hours.

From calculations derived from the tests, it was determined that SBX-34 had passed the requirements for self-heating, thermal stability, and slow cookoff. The calculation for the predicted critical temperature, T_m, was 124°C for a 12-inch-diameter warhead and 118°C for an 18-inch-diameter, 2,000-pound Mk 84 general purpose bomb.

SBX-34 IN AIRCRAFT FUEL FIRE

In addition to being subjected to individual thermal test procedures and analyses, SBX-34 was also cast into an unlined, full-scale Zuni Mk 24 warhead and engulfed in a 750-gallon aircraft fuel fire. Temperatures reached 1094°C (~2,000°F) in just over a minute. Soon after, the Zuni round deflagrated and ruptured in essentially two large fragments. No small fragments were produced in this cookoff reaction. The fact that this round did not detonate was indeed a good indicator that this explosive formulation is a good candidate for use as an insensitive munition.

EXPOSURE TO 100% RELATIVE HUMIDITY

What is the effect of long-term exposure to moisture on SBX-34? To answer this important question, three small samples of SBX-34 were placed in a covered glass desiccator containing ~300 mL of water. The desiccator was then placed in a steam oven set at ~52°C. The explosive samples were observed over a period of 8 days, and any physical dimensional change was noted. This exposure to 100% relative humidity was performed with the full realization that SBX-34 was an explosive composition with a water soluble and hydrolyzable binder. The results of the high humidity exposure test showed that the average weight percent gain after 3 days was 4.02%; after 8 days the average was 5.92%.

The 5-6% weight gain from moisture was expected. Surprisingly, however, the high moisture environment seemingly had very little effect on the physical strength of the samples. No slumping or other adverse effect on the samples was noted during the entire 8-day exposure period.

Three other solid cylindrical samples of SBX-34 (approximately 86 grams each, with density of 1.567 g/cm^3) were subjected to the identical moisture environment for up to 22 days. After 10 days, physical dimensions and weights increased slightly with a corresponding drop in density.

After 22 days of 100% humidity exposure, the cylinders became more saturated and binder degradation more obvious. The samples were measured again. Weights had increased (more water absorbed) along with slight increases in volume. Weight gains averaged 3.82%. Density averaged 1.564 g/cm^3—not much of a change from its original value.

It is encouraging to report that SBX-34, despite being a polyurethane-type explosive, will not easily undergo hydrolytic attack in the presence of moisture alone. Rather, it is designed to degrade *only* under controlled treatment with dilute ammonia or acid in explosives recovery.

The mechanism of binder degradation can be depicted by the chemical diagram shown in Figure 8.

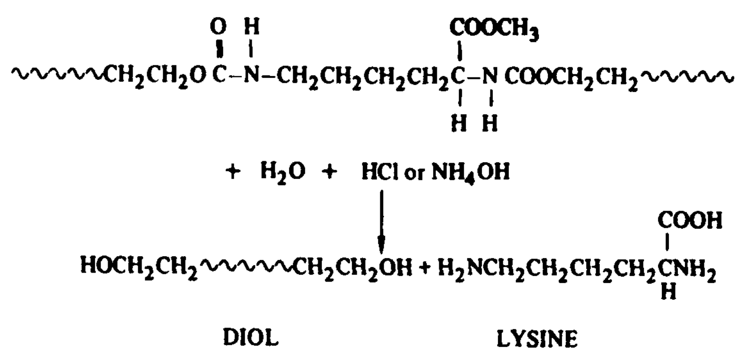

FIGURE 8. SBX-34 Polyurethane Binder.

The two products of binder breakdown, the diol and lysine, are considered safe and non-polluting, well within the scope and objective of this program.

BINDER DEGRADATION AND EXPLOSIVE RECOVERY

Laboratory studies of RDX recovery from SBX-34 were also conducted with excellent results. Samples of SBX-34 (12.03, 12.41, and 6.50 grams) were immersed in ~50 mL of dilute (5%) ammonium hydroxide for a day, then rinsed, filtered, and dried overnight in a vacuum oven at 80°C. Results showed that the percentage of recovered RDX from each of the three samples equaled 82.46, 82.35, and 82.46%, respectively, (SBX-34 contains a total of 82% RDX in a blend of four classes). The fraction of a percent in excess weight might be attributed to adsorption of some residual binder on the RDX solids. It is quite conceivable that, in scale-up, the recovered blend of RDX could have been recycled to prepare another batch of explosive. The only other ingredients needed would have been the binder and curative. A cost advantage is definitely achievable.

Later, in a high-pressure water washout facility at another location, this explosive was effectively removed in only a few seconds from a simulated warhead round. Rapid and safe demilitarization was aptly demonstrated.

CONCLUSIONS

The feasibility of composition SBX-34 in serving as an acceptable main charge explosive, yet contributing significantly to our nation's environmental pollution abatement efforts, was demonstrated. This investigation established that this composite polyurethane/RDX system, which is also easily degradable, can be used to formulate very adequate high explosives. Although some of the mandatory test requirements called for in NAVORD OD 44811 were not fulfilled in their entirety because of insufficient numbers of test samples, the values obtained from those limited tests were considered to be valid. Great efforts went into proving that this type of composition is relatively insensitive from the thermal standpoint. We believed that SBX-34 could be qualified as a main charge explosive for the Navy. So much so that SBX-34 was redesignated composition PBXC-125 at the termination of the program (References 6 and 7).

REFERENCES

1. Executive Order 11507 of 4 February 1970. ". . . the Federal Government, in the design, operation, and maintenance of its facilities, shall provide leadership in the nationwide effort to protect and enhance the quality of our air and water resources."

2. OPNAVINST 6240.3E, 5 July 1977.

3. Executive Order 12088, "Federal Compliance With Pollution Control Standards," 13 October 1978.

4. Naval Ordnance Systems Command. *Safety and Performance Tests for Qualification of Explosives*, prepared by the Naval Weapons Center. Washington, D.C., NAVORD, 1 January 1972. (NAVORD OD44811, Volume 1, publication UNCLASSIFIED.)

5. Naval Weapons Center. *Thermal Analyses Studies on Candidate Solid JPL Propellants for Heat Sterilizable Motors*, by Jack M. Pakulak, Jr. and Edward Kuletz. China Lake, Calif., NWC, July 1970. (NWC TP 4258, publication UNCLASSIFIED.)

6. Naval Weapons Center. *Water Soluble and Hydrolyzable Binder Explosives*, by B.Y.S. Lee. China Lake, Calif., NWC, February 1982. (NWC TP 6313, publication UNCLASSIFIED.)

7. U. S. Patent No. 4,293,352. *Degradable Binder Explosives*, by Benjamin Y. S. Lee, Russel Reed, Jr., and Roger L. Miller, 6 October 1981.

GLOSSARY

D22-45	Hydroxyl-terminated polyester diol with a polyethylene glycol adipate backbone; f = ~3 (Witco Chemical Corp.)
DTA	Differential thermal analysis
f	Functionality
HMX	Cyclotetramethylenetetranitramine
Hylene W	4,4'-diisocyanatodicyclohexyldiphenylmethane (E. I. duPont de Nemours and Co.)
L-35	Diol, 50% ethylene oxide-capped polyoxypropylene glycol (BASF Wyandotte Corp.)
LDIM	Lysine diisocyanate methyl ester (Dexter Midland Corp., Toray Industries)
NCO	Isocyanate
OH	Hydroxyl
PBX	Plastic-bonded explosive
PEG	Polyethylene glycol
RDX	Cyclotrimethylenetrinitramine
SBX	Soluble binder explosives (denotes series assigned to formulations in this program)
TGA	Thermogravimetric analysis
VTS	Vacuum thermal stability
ϕ_3Bi	Triphenylbismuth
YA 23-4	Adipate polyester with 79% polyethylene glycol content, hydroxyl f = 2.33 (Witco Chem. Corp.)

DESIGN AND FULL SCALE TRIAL OF A LARGE SPAN ARCH EXPLOSIVE STOREHOUSE

by
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ABSTRACT

As part of an investigation into the development of more cost effective explosives storehouses, the Australian Department of Defence have conducted a number of trials to confirm the performance of large span circular arch explosives storehouses at Woomera.

The storehouses consisted of a proprietary profiled light gauge steel arch faced with sprayed concrete. The light gauge steel shell thus acted as expendable formwork and also contributed to the reinforcement of the arch. The resulting structure was covered with earthfill in accordance with standard specifications.

In two previous trials, three 13 m span receptor arch structures successfully withstood the blast effects generated by the detonation of 75,000 kg TNT. More recently the performance of a new 23 m span arch explosives storehouse was examined. The new receptor was located at minimum side to side separation distance from one of the 13 m arch structures remaining from the earlier trials.

The receptor structure survived the blast with only limited damage. Measured blast loads on the receptor, although less than the blast load criteria adopted in the design, are considered representative of the blast load environment to be expected. Analytical response predictions were found to be broadly in agreement with the measured values. The structure has now been approved for use as an igloo by the Australian Defence Forces.

1. INTRODUCTION

In view of the proposed redevelopment of a large proportion of Defence explosives storage facilities, considerable attention is being paid to the development of cost effective explosives storehouses (ESH). A number of trials, in May 1990 (Ref.1), September 1990 (Ref. 3) and October 1991 (Ref. 3), have been conducted to assist in this process. The most recent trial is the subject of this paper. In this trial the behaviour of a large span arch explosives storehouse subjected to the effects of a detonation of 75,000 kg TNT at minimum 'side to side' separation distance was examined. The principal aim of this trial was to validate the design of the new large span arch structures as a hardened receptor structure for Explosives Storehouses spaced at D3/D4 distances (Ref. 5).

The receptor explosives storehouse consisted of an earth covered concrete (shotcrete) arch lined internally with a deep rib light gauge sheeting produced by SPANTECH. A typical plan and elevation of the structure appear as Figure 1. The unusual double arch form was used to permit a reduction in the building footprint (length)[1]. The

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1 The smaller arch at the rear can be fitted within the earth traverse generated by the major arch whilst maintaining the minimum earth cover at all points. Thus the extra 3 m internal length does not add to the total building length.

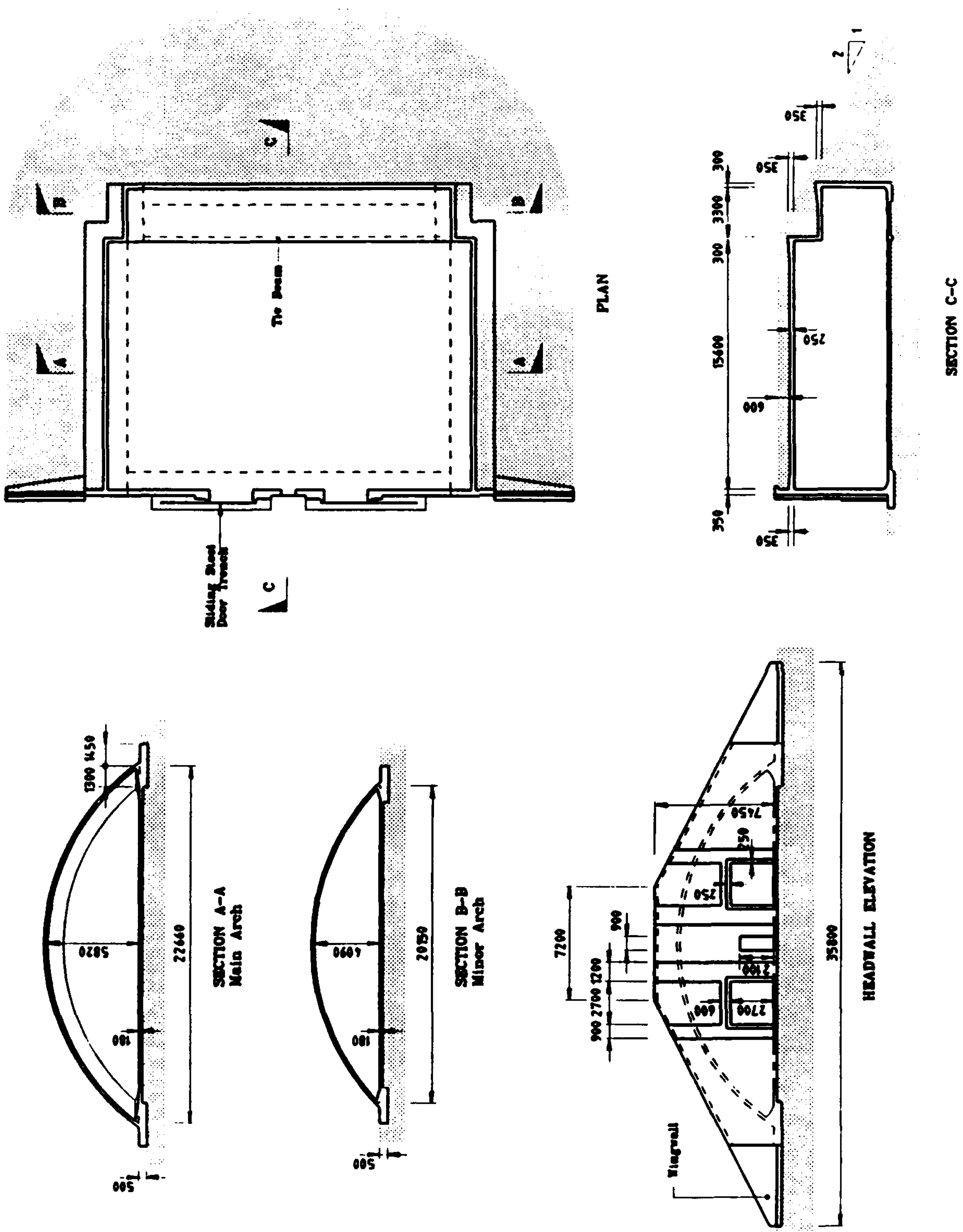

Figure 1. Large Span Explosive Storehouse

reinforced concrete headwall and endwalls are of conventional construction - the internal SPANTECH sheeting acts both as permanent formwork, thereby speeding construction, and also as arch reinforcement. The configuration adopted permits the storage of some 380 pallets.

The arch is constructed using light gauge (1.0 mm G300 steel plate) profiled galvanised sheeting which is then covered with a layer of 32 MPa shotcrete and lightly reinforced with steel mesh. The shotcrete thickness varies from 250 mm at the centre of the arch to 350 mm at supports. The profiled steel sheeting consists of curved trays nominally 300 mm wide with 110 mm ribs which are mechanically interlocked. Once erected the steel arch is self supporting. With the aid of propping along the centre of the arch, the arch can support the selfweight of the applied shotcrete. The headwall, the intermediate wall between the two arches and the end wall are constructed monolithically with the arches and so provide substantial support to them.

In addition to ensuring that the new receptor was capable of resisting the normal design and construction loads, the structure was designed to resist the effects of a 75,000 kg detonation at D3/D4 distances. For the side-on configuration the following blast loads were adopted for the arch crown.

Peak Side on Pressure	P_{so}	=	303	kPa
Blast Impulse	i_s	=	4272	kPa.ms
Blast Duration	t_s	=	28	ms
Blast Wave Velocity		=	640	m/s

For points either side of the crown, the blast loads on the arch were adjusted to approximately account for,

- the effect of slope of the earth cover on the reflected pressures experienced.
- the decay of the pressure wave with distance from the source

Design review of the headwall and doors was based on TM5-1300 (Ref. 5) whereas the arch itself was reviewed using a linear elastic finite element package.(Ref. 6). In view of the substantial circumferential compressive stresses developed in the arch and the limited capacity of the shell in these circumstances to behave in a ductile manner, the review basis adopted was to ensure that the combined axial and flexural loads remained substantially within the ultimate load interaction diagram for the section.

2. TEST CONFIGURATION

The test configuration adopted for the trial is set out in Figure 2. The donor structure used in the trial was one of the existing 13 m arch ESH trialled previously. The donor consisted of a 250 mm reinforced concrete arch with a 300 mm rear wall. The headwall was of 350 mm reinforced concrete and incorporates 900 x 500 buttresses at the door. A sliding steel blast door was centrally located. Earth cover geometry was in accordance with ESTC Leaflet No. 6, Ref. 4., namely 600 mm cover at the roof with a 1:2 slope back to natural surface. The fill consisted of the soil readily available at the site - a heavy clay. Details of this structure appear in Reference 1.

Although the use of a 13 m arch as the donor meant that the trial did not exactly represent the blast environment that might be expected from a 'large span SPANTECH' ESH it was considered that the blast loads were likely to be acceptable as a basis for judging the performance of the receptor.[2]

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2 As the internal volume of the donor SPANTECH structure is only 520 m^3, the effective charge density, assuming 75000 kg HE, is 144 kg/m^3. The internal volume of the new receptor structure is 1650 m^3 and so, for 75000 kg, the explosive loading density is very much less. The blast loads generated in this trial should therefore be more severe than those likely to be generated by a detonation in a 23 m ESH.

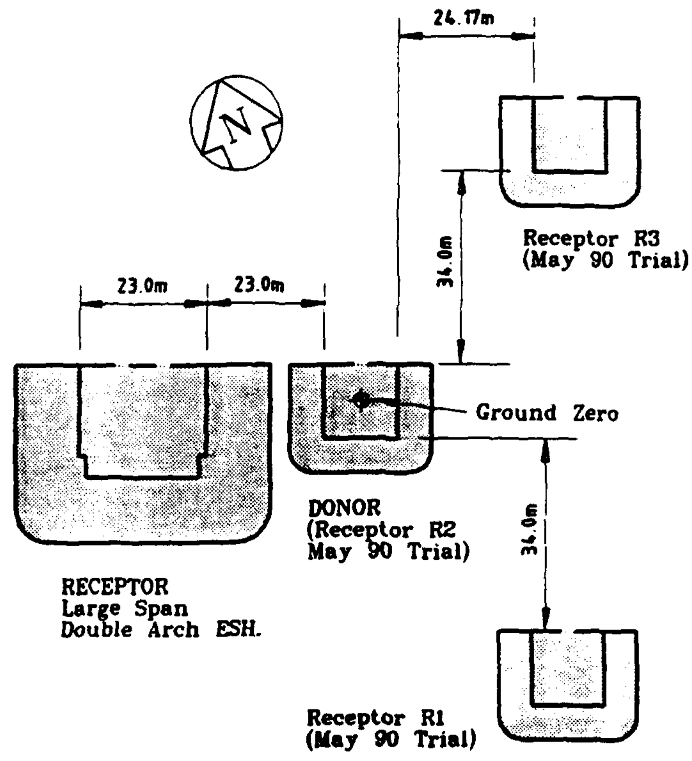

Figure 2. ESH Donor/Receptor Trial. Site Plan.

2.1 EXPLOSIVE CHARGE

The donor charge consisted of 120 pallets of boxed mines, arranged in a roughly semi-cylindrical configuration as shown in Figure 3. The priming charge geometry was determined to ensure a complete and instantaneous detonation, thereby eliminating the risk of 'throw outs' or unexploded mines contaminating the site.

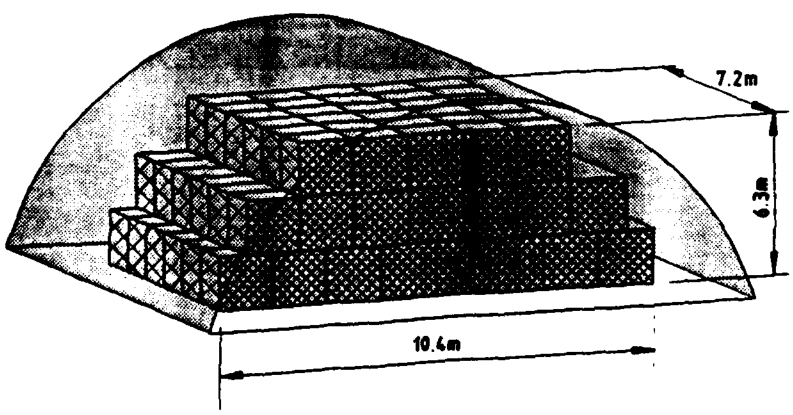

Figure 3. Explosive Stack Configuration.

2.2 INSTRUMENTATION

Explosives Ordnance Division (EOD), of Materials Research Laboratory (MRL) was tasked with measuring the blast overpressures on and inside the receptor structure as well as the structural accelerations and displacements of the receptor building. Additional details regarding the EOD instrumentation is provided in the EOD report (Ref. 8).

Waterways Experiment Station (WES), US Department of Army Corps of Engineers supplemented the near field instrumentation effort by locating a number of pressure transducers on the new receptor and also on the receptors remaining from earlier trials. In addition WES provided the instrumentation for the far field pressure investigation. Additional details regarding the WES instrumentation is provided in the WES preliminary report (Ref. 7).

2.2.1 Far Field Measurements

Gauge lines for the far field measurements were set out with respect to the nominal centre of the donor structure as displayed in the following figure. Three radial lines were used - lines at 0° (north), 90° (east) and 180° (south). (The 0° line is taken as the direction forward of and perpendicular to the original donor headwall). The nearer gauges are located at standard quantity distances and thus the distances relate to the distance from the structure walls or footing.

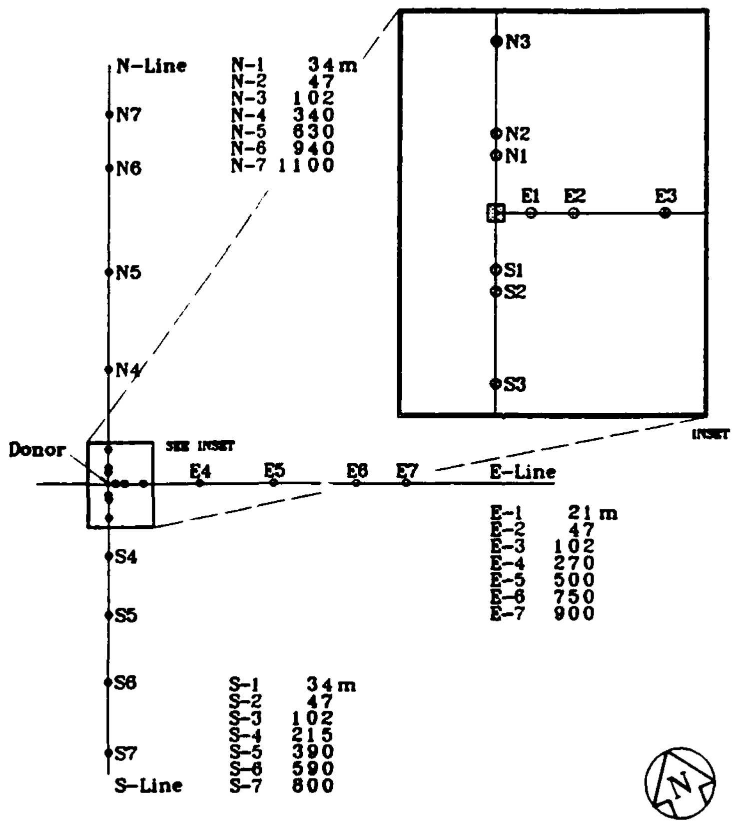

Figure 4. Layout of Far Field Pressure Gauges.

2.2.2 Near Field Instrumentation

In order to assess the behaviour of the receptor structure under the blast load, instrumentation was located on and inside the receptor structures to record the blast pressures applied to the structure and also the response of the structure to these loads.

A total of 13 pressure gauges - comprising 9 on the roof, 3 on the headwall and one internal were deployed by EOD as shown in Figures 5 and 6 respectively. An additional eight near field pressure gauges were deployed by WES. Four were located on and adjacent to the 13 m ESH remaining from earlier trials. The other four were located on and adjacent to the new receptor

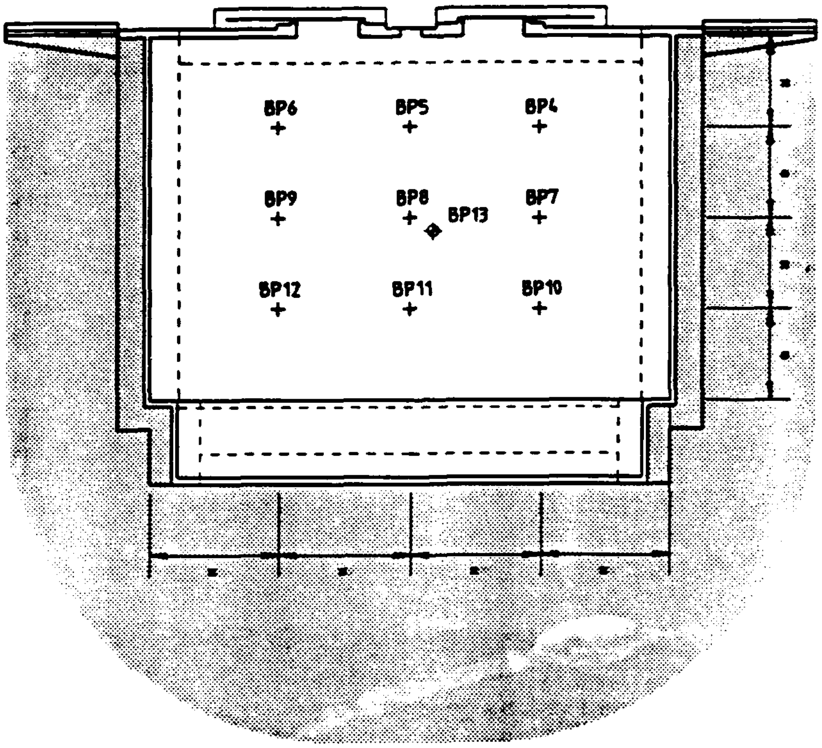

Figure 5. Plan View of Near Field Pressure Gauges on the Large Span Receptor Roof.

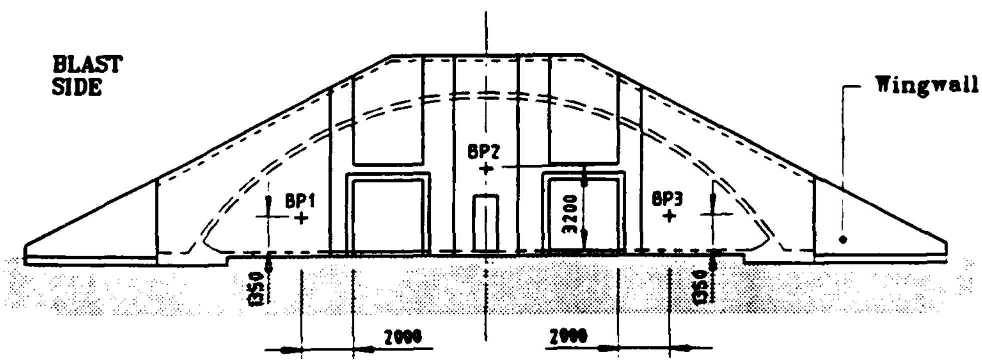

Figure 6. Layout of Pressure Gauges on the Receptor Headwalls.

In view of the difficulties in the former trials in determining the displacement response of the arch from accelerometer records, the large span Receptor was instrumented with a number of Sangamo UAC50 Linear Variable Displacement Transducer (LVDT). The transducers are an AC captive armature type with a $\pm$ 50 mm stroke and fitted with a universal joint at each end. The displacement transducers were connected to softly sprung inertial mounts in order to obtain an indication of the absolute displacement of the attachment point. The

transducers were generally arranged in pairs as shown in Figure 7, to measure vertical and horizontal displacements on the arch.

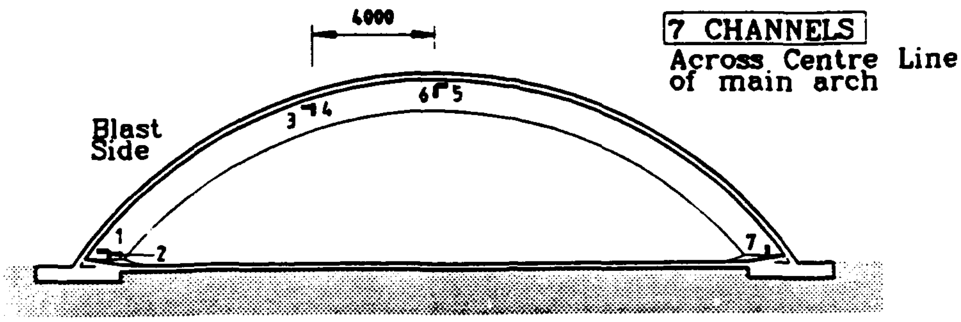

Figure 7. Location of Displacement Transducers. (Main Arch)

3. TEST RESULTS

The donor charge was detonated at approximately 9:30 am on 26 October 1991. Based on the instrumental results for the far field pressures it is considered that complete detonation was achieved. The detonation resulted in the complete demolition of the donor structure - all that remained was the crater (and extensive earth uplift around its perimeter). The maximum apparent depth of the crater is approximately 2.0 m with a 'diameter' varying from approximately 25 m to 30 m. Although comparable in size to those observed in the former trials the resultant crater is very much less extensive than might be expected from standard correlation expressions, eg as in CONWEP Ref. 9, for a free field surface detonation.

The large span receptor survived the detonation with only minor damage. The external face of the structure was not even blackened by soot from the fireball (notwithstanding its proximity to the donor). An examination of the headwall revealed numerous fine cracks along the support provided by the arch and headwall buttress. These cracks are considered to be consistent with elastic response rather than permanent deformation.

Of greatest concern was the behaviour of the major arch. Whilst the major arch showed no signs of significant change to its internal profile it was apparent that some significant deformations had been experienced. The SPANTECH lining was 'drummy' over most of the arch surface - indicating that the sheeting was no longer in intimate contact with the concrete. In addition for the footing closest to the blast, significant crimping of the lining was experienced at the arch-footing junction.

The most significant damage experienced was the failure of the main doors to the ESH under rebound. These were discovered lying on the ground in front of the headwall after the blast. Although the doors were subjected to substantial blast loads and suffered some permanent deformation (approximately 100 mm central), the failure was not due to inadequate design but rather due to faulty workmanship in the fixings of the rebound restraints.

4. INSTRUMENTAL RESULTS

Two different systems were used as the basis for time zero. EOD used a 'breakwire' wrapped around the explosive. WES used the electrical firing signal. As the WES results were triggered off the electrical firing signal, rather than the break wire trigger used by EOD a timing correction was required.

4.1 PRESSURE MEASUREMENTS

The WES far field radial pressures are summarised in Table 1 together with estimates for an equivalent free field hemispherical detonation. Note that the distances recorded here have been adjusted to yield distances from Ground Zero (i.e. centre of the donor structure) to the gauge point. The results obtained for peak pressure are plotted against the CONWEP estimates in Figure 8. The instrumental results appear low at short scaled distances and although they appear to converge at higher scaled distances it should be noted that they are still only 60 to 70% of the free field values.

Transducer	Distance from GZ (m)	Arrival Time (ms)		Peak Pressure (kPa)		Impulse (kPa. ms)		Positive Phase Duration (ms)	
Northern Line									
N1	40.5	n.r.	(18.3)	n.r.	(1477)	n.r.	(9881)	n.r.	(63.7)
N2	53.5	n.r.	(30.5)	n.r.	(806)	n.r.	(8543)	n.r.	(93.2)
N3	108.5	n.r.	(114)	n.r.	(161)	n.r.	(4467)	n.r.	(100)
N4	346.5	n.r.	(707)	n.r.	(19.6)	n.r.	(1579)	n.r.	(189)
N5	636.5	n.r.	(1511)	n.r.	(8.63)	n.r.	(875)	n.r.	(230)
N6	946.5	2545	(2402)	4.00	(5.24)	475	(593)	n.a.	(258)
N7	1106.5	3050	(2867)	3.24	(4.28)	375	(508)	n.a.	(269)
Eastern Line									
E1	27.5	32.5	(9.33)	517	(3124)	4260	(7443)	n.a.	(19.3)
E2	53.5	71.7	(30.5)	237	(806)	3700	(8543)	n.a.	(93.2)
E3	108.5	182	(114)	88.3	(161)	2520	(4467)	n.a.	(100)
E4	276.5	603	(519)	21.6	(27.5)	1500	(1953)	n.a.	(176)
E5	506.5	1246	(1147)	5.95	(11.6)	867	(1093)	n.a.	(214)
E6	756.5	2110	(1853)	5.22	(6.95)	565	(739)	n.a.	(243)
E7	906.5	2547	(2286)	4.00	(5.54)	482	(619)	n.a.	(255)
Southern Line									
S1	40.5	44.2	(18.3)	416	(1477)	3460	(9881)	n.a.	(63.7)
S2	53.5	62.8	(30.5)	213	(806)	3260	(8543)	n.a.	(93.2)
S3	108.5	178	(114)	n.r.	(161)	n.r.	(4467)	n.a.	(100)
S4	221.5	461	(375)	24.3	(39.7)	1800	(2391)	n.a.	(163)
S5	396.5	940	(843)	9.58	(16.1)	1050	(1387)	n.a.	(198)
S6	596.5	1644	(1398)	7.02	(9.37)	581	(932)	n.a.	(226)
S7	806.5	2240	(1997)	3.95	(6.42)	435	(695)	n.a.	(247)

n.r. = no result n.a. = not available

Table 1. Summary of Far Field Pressure Measurements

Pressure Measurements taken on the new receptor, and also on the existing small span storehouses are summarised in Table 2 for the arch roof and headwall. Results are provided for the time of arrival, peak pressure, impulse and equivalent duration. To provide a frame of reference for these values the corresponding estimates for a hemispherical detonation are included in brackets. The results reported by WES are incorporated in this table also. The results obtained in this table are plotted in the next two figures. In view of the small range of scaled distances involved a linear plot scale has been used here.

Plots of the pressure measurements and positive phase impulse data together with CONWEP estimates have been plotted in Figure 9. The comparison is not strictly appropriate as the CONWEP estimates are based on a plane hemisphere whereas most of the measured near field values are on, or near, the crests of earth mounds or on slopes either facing to or away from the blast. As expected, in view of the significant effect of the details of the donor breakup on the blast environment, the results show considerable scatter and are significantly below the CONWEP line.

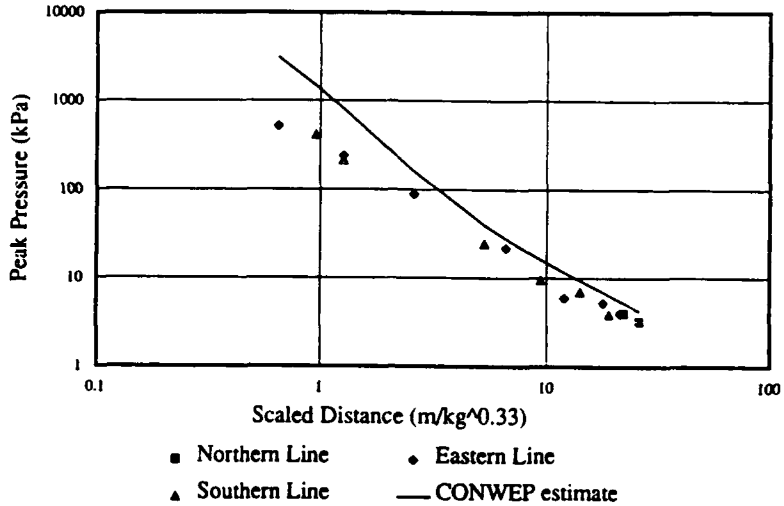

Figure 8. Comparison of Measured and Estimated Far Field Pressures.

Transducer	Distance from GZ (m)	Arrival Time (ms)	Peak Pressure (kPa)	Impulse (kPa. ms)	Equivalent Duration (ms)
EOD Results					
Headwall[3]					
BP1	35.2	n.r. (14.3)	n.r. (1965)	n.r. (8796)	n.r. (8.9)
BP2	42.3	52.4 (19.8)	436 (1348)	4160 (9790)	19.1 (14.5)
BP3	49.4	64.2 (26.3)	352 (963)	3400 (9059)	19.3 (18.8)
Arch Roof					
BP4	36.3	44.2 (15.1)	>932 (1848)	n.r. (9041)	n.r. (9.8)
BP5	42.0	51.8 (19.6)	474 (1368)	2200 (9809)	9.3 (14.3)
BP6	47.7	62.0 (24.7)	240 (1041)	2350 (9264)	19.6 (17.8)
BP7	36.0	44.9 (14.8)	>930 (1879)	5490 (8973)	<11.8 (9.5)
BP8	41.8	52.6 (19.4)	573 (1382)	2220 (9821)	7.7 (14.2)
BP9	47.5	62.7 (24.5)	258 (1050)	2090 (9288)	16.2 (17.7)
BP10	36.3	45.9 (15.1)	756 (1848)	5340 (9041)	14.1 (9.8)
BP11	42.0	53.9 (19.6)	516 (1368)	2640 (9809)	10.2 (14.3)
BP12	47.7	63.8 (24.7)	251 (1041)	2080 (9264)	16.6 (17.8)
Internal					
BP13	41.8	n.r. (19.4)	n.r. (1382)	n.r. (9821)	n.r. (14.2)
WES Results					
NFP1	21.5	28.4 (6.23)	800 (4727)	6190 (7005)	15.5 (2.96)
NFP2	41.6	50.3 (19.2)	323 (1396)	2400 (9832)	14.9 (14.1)
NFP3	42.1	50.0 (19.7)	280 (1362)	4570 (9803)	32.6 (14.4)
NFP4	66.9	62.6 (46.3)	175 (484)	4770 (7014)	54.5 (28.9)
NFP5	61.6	88.9 (39.7)	255 (585)	4160 (7570)	32.6 (25.9)
NFP6	61.0	60.9 (39.0)	279 (598)	2510 (7638)	18.0 (25.5)
NFP7	57.0	n.r. (34.3)	351 (699)	>2750 (8108)	>15.7 (23.2)
NFP8	62.8	83.9 (41.2)	176 (560)	3360 (7438)	38.2 (26.6)

n.r. = no result

Table 2. Summary of Near Field Pressure Measurements

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3 **Note that the CONWEP estimates quoted for the headwall are 'side-on' values.**

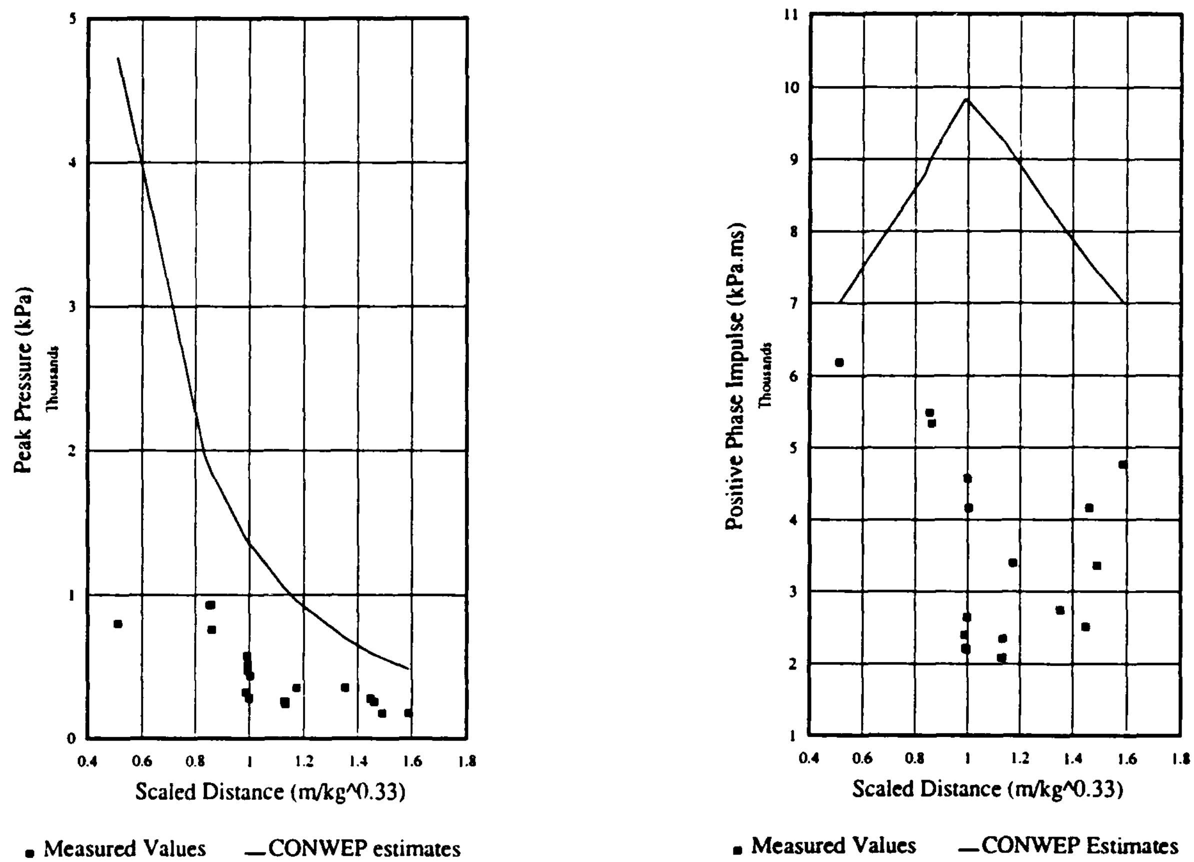

Figure 9. Comparison of Near Field Measured and Estimated Peak Pressure and Impulse Measurements.

4.2 STRUCTURE RESPONSE MEASUREMENTS

Instrumental measures of the ground shock and structure response were determined from the accelerometer and displacement transducer records.

4.2.1 Arch Response

Arch response data was obtained principally from the displacement transducers, however some supplementary accelerometer data was also obtained. Only the displacement transducer results are discussed here.

Six of the twelve displacement transducers, namely Channels 1 to 4, 6 and 8, were damaged during the blast due to the ground shock displacements over-ranging the transducers. Limit stops had been installed to prevent excessive displacement however these had only been partially successful.

Notwithstanding the damage sustained, all of the transducers functioned satisfactorily until they were over-ranged which, generally, can be detected as a relatively abrupt discontinuity in the displacement trace. This typically occurred some 150 ms to 200 ms after the detonation. It is considered that up to this point the displacement traces provide a reliable indication of the absolute motion[4] of the point of the structure to which the transducer was connected.

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4 Which consists of motion due to structure deformation and ground motion.

As an example Figure 10 compares the horizontal displacements recorded along the centre of the main arch. As noted earlier Channel 1 is located adjacent to the arch footing (blast side), Channel 6 is located at mid span, and Channel 3 is located at an intermediate point 4 m from Channel 6. The three traces can be seen to exhibit similar behaviour in the first 150 ms. Note that Channel 1 initially experiences a motion towards the blast and that the characteristics of this motion are reflected in the traces for Channels 3 and 6.

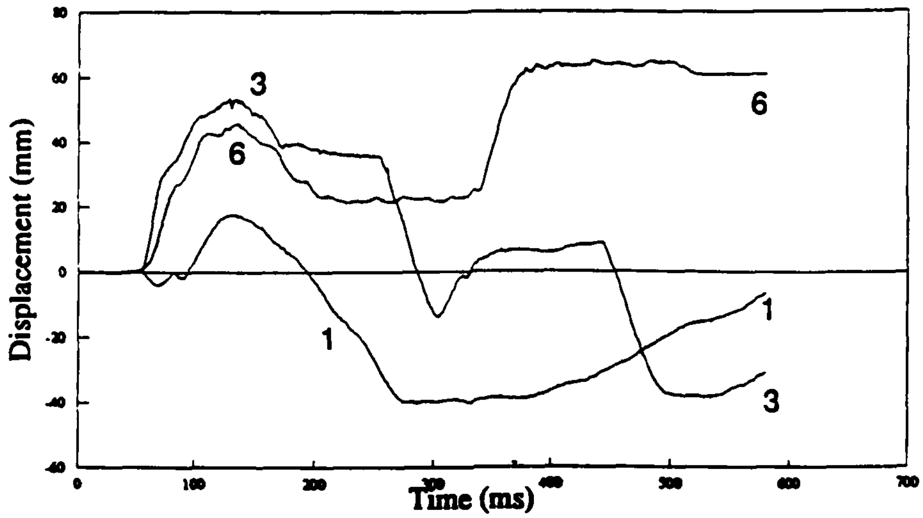

Figure 10. Displacement (horizontal) traces for Channels 1,3 and 6.
(Note: Positive displacements indicate motion of the attachment point away from blast)

Arch Deformations

The arch deformations are estimated by obtaining the displacements of points on the arch relative to the arch footings thus removing any rigid body rotations due to ground deformation. The following table summarizes estimates of the measured arch deformation for the three locations instrumented (three pairs of transducers). Note that, as in the figures, positive horizontal displacements correspond to motion of the attachment point away from the blast, positive vertical motions correspond to downwards motion of attachment point.

Transducer	Attitude	Significant Displacement Peaks (mm)	Time at which Maxima Occurred (ms)
Ch 3	Horizontal	+35, +43	80, 100
Ch 4	Vertical	+35	85
Ch 5	Vertical	-4.2	100
Ch 6	Horizontal	+35	106
Ch 10	Horizontal	+13	94
Ch 11	Vertical	-7	100

Table 3. Large Span Receptor - Arch Displacements.

5. STRUCTURAL RESPONSE PREDICTIONS

In order to assess the validity of the structural models adopted for the design of the facility, and thus assess our capacity to predict the behaviour of the arch, a number of analyses of the Receptor were performed. A linear

elastic finite element model was used to examine the behaviour of the structure to the instrumentally determined blast overpressures.

The analysis was performed using the program ALGOR/SUPERSAP. A model of the arch, is shown in Figure 11, in which the soil, modelled using 8 noded brick elements, has been partly removed to reveal the shell underneath.

Although the model developed is computationally intensive - entailing approximately 10 hours processing time on a 33 Mhz 486 microcomputer - it must be recognised that the model is nevertheless still limited in its capacity to predict the true response of the system. The results therefore should be seen only as an approximation to the real behaviour.

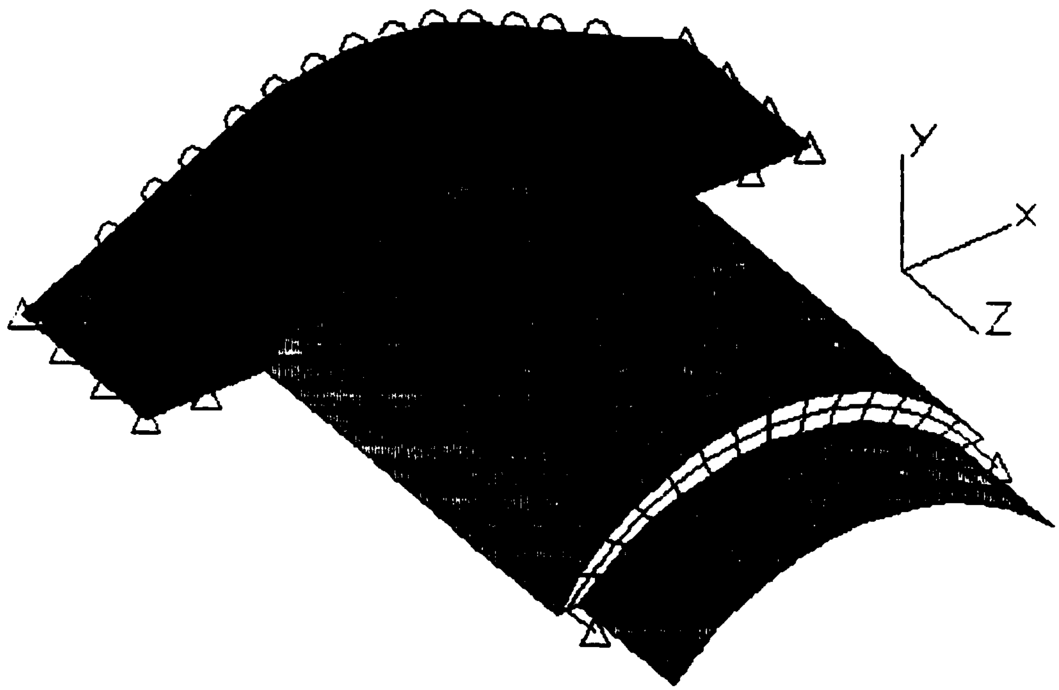

Figure 11. Structural Model Adopted for 'Side-On' Case.

5.1 ARCH PROPERTIES

Conventional 4 node plate elements were used to model the reinforced concrete arch. The arch footing was assumed to be elastically supported using linear elastic boundary elements. Rotational springs (based on the soil properties subsequently noted) were used to model the rotational stiffness of the soil - which, for the short duration loads involved, is considered appropriate. In addition soil springs were used to provide vertical and horizontal restraint.

Because of the deep profile SPANTECH sheeting in the soffit of the arch, the arch section will exhibit different section properties depending on the sense of flexure induced. That is, in the longitudinal direction, the effective thickness of the shell may vary from 250 mm to 140 mm depending on the whether the top surface is in tension or compression. As this effect cannot be modelled with a linear elastic finite element analysis a uniform section has been used throughout. However to approximately account for this reduced flexural stiffness relative to the axial stiffness, the model has been stretched by a factor of two in the longitudinal direction. The effect can also be partially accounted for in the load capacity checks.

Load capacity checks were performed using an interaction diagram derived for typical sections. As an adequate model for the prediction of the ultimate strength behaviour of reinforced concrete slabs to a general load (axial stresses in both directions, shear stresses, bending in both directions plus twisting) does not exist, it is necessary to resort to a uniaxial environment to determine the capacity of the section. Actions in the perpendicular direction are thus assumed not to significantly affect the behaviour in the principal direction. Also, in the circumferential direction, the effective thickness is unaffected by the sense of flexure.

As the 28 day test results for the shotcrete yielded a mean strength of 39 MPa - a dynamic concrete strength of 45 MPa and a dynamic elastic modulus of 32000 MPa was used in the analysis. A value of 500 MPa was adopted for the dynamic yield strength of the reinforcement - which represents a 20% increase over the static value.

It should be noted that points falling outside the zone defined by the interaction diagram do not necessarily imply collapse of the arch. A number of supplementary issues must be considered, such as the,

- spatial extent of the overloaded region
- duration for which an element is overloaded
- low axial stresses, high flexural loads

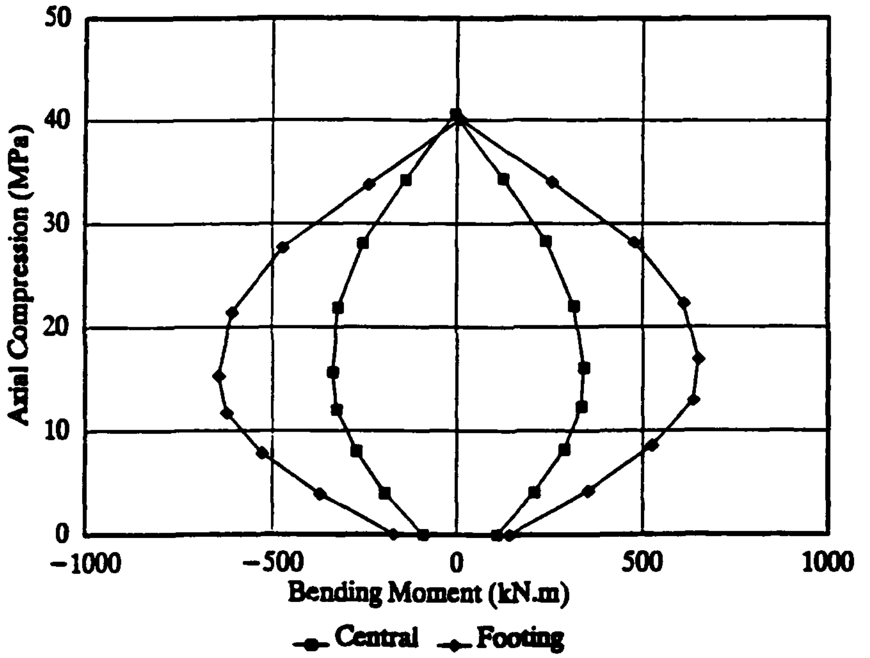

Figure 12. Interaction Diagram for Arch - Circumferential Direction.
(Positive moments produce tension on bottom face of arch)

5.2 SOIL PROPERTIES

Based on a geotechnical investigation, the following soil properties were adopted for the earth cover,

Soil Shear Wave Velocity	=	142 m/s
Soil Compression Wave Velocity	=	350 m/s
Poisson's Ratio	=	0.4
Soil Density	=	1800 kg/m^3

From these values the elastic and shear moduli were estimated using standard theory. The values adopted in the analysis were,

Soil Elastic Modulus	=	102 MPa	say 100 MPa
Soil Shear Modulus	=	36.4 MPa	

In view of the small deflections experienced by the structure, during the passage of the blast wave, it is considered that the use of elastic properties for the soil is reasonable.

5.3 BLAST LOADS

The blast loads applied in the analysis were obtained from a curve fit to the average measured values. The next figure, Figure 13, depicts the variation in peak pressure with distance assumed in the analysis. Averages of the measured values appear on this figure also. The fit to these measured values is clearly good although extensive extrapolation outside this range is involved.

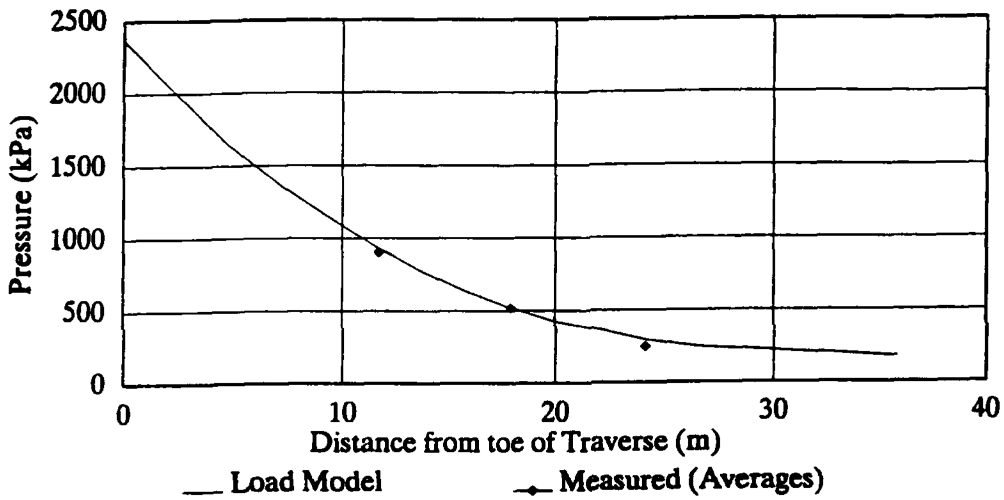

Figure 13. Assumed variation of Peak Pressure compared with measured values.

5.4 DYNAMIC ANALYSIS RESULTS

Analysis entailed the direct integration of the equations of motion using 500 time steps of 0.20 ms duration. (Total analysis duration = 100 ms). It should be noted that as the analysis is a linear elastic one - the oscillatory response beyond the first excursion becomes increasingly unreliable and should be treated with caution.

5.4.1 Arch Displacements

A comparison of the analytical and measured response indicates only moderate agreement[5]. Nevertheless the displacement response of the structure summarised hereunder exhibits a number of features consistent with the

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[5] In order to permit comparison of measured and predicted response a common time base is required. The analytical predictions are based on an analysis in which the shock front arrival at the crown of the arch matches the average measured value - 52.6 ms.

measured displacement response. Whilst the maximum deflections predicted are comparable to those measured the details of their variation with time is often quite dissimilar. Although a number of the assumptions implicit in the analytical model have been tested for their capacity to influence the results it has not been possible in the time available to achieve an entirely satisfactory result.

Typical plots of displacement of the arch as a function of time for a point on the arch model 84 and the corresponding transducer appear in the next figure. The predicted peak displacements in the vertical and horizontal direction are only 26 mm and 38 mm compared with measured values of 43 and 42 mm respectively. Nevertheless the displacement traces exhibit some consistent features - for example - the effective period of vibration appears comparable.

In both the vertical and horizontal traces the measured response indicates a later but much more abrupt rise in deflection. The predicted vertical displacement exhibits a number of significant harmonics - which are not at all reflected in the transducer result. Although not presented here the predicted displacement plots for a point somewhat lower down on the arch are in reasonable agreement with the measured values for Channels 3 and 4. These discrepancies suggest that the analytical model does not capture the physical behaviour entirely satisfactorily.

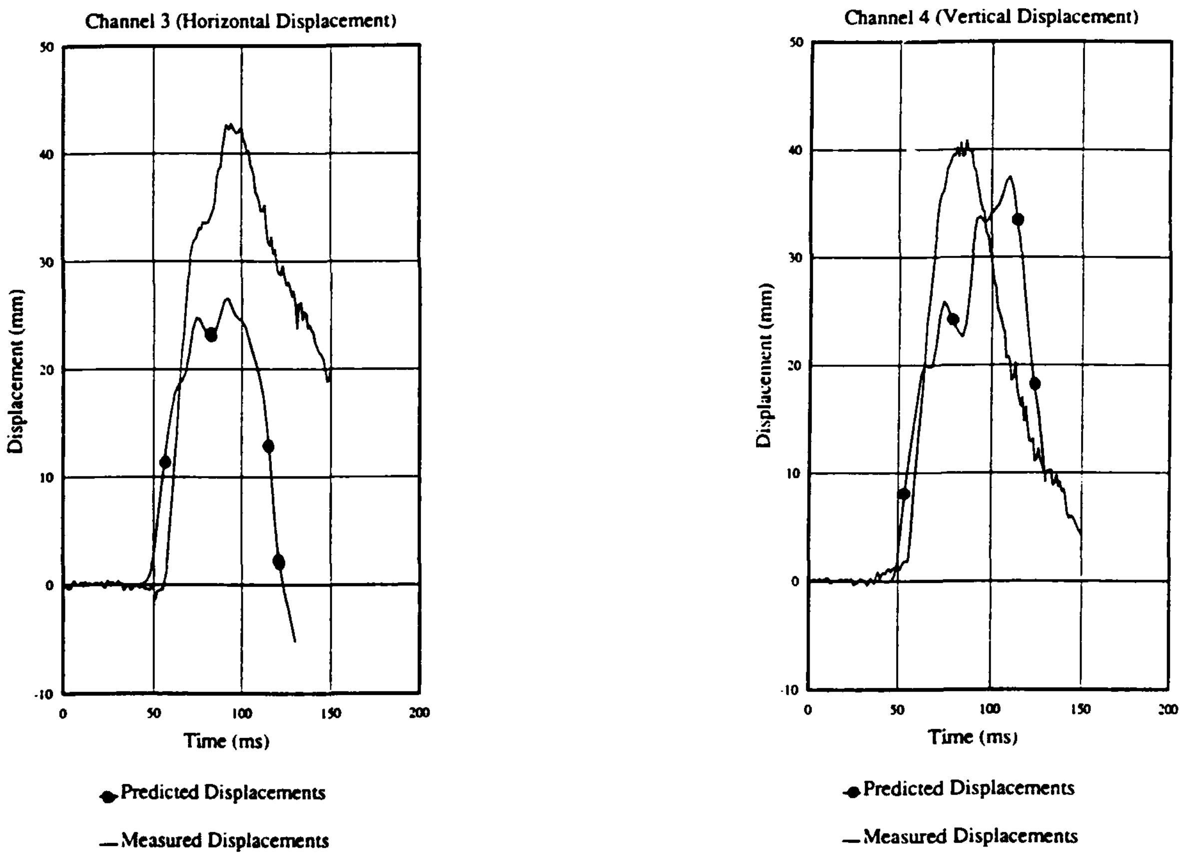

Figure 14. Arch Displacement vs Time - Channel 3 and 4

5.4.2 Arch Stresses

Stresses developed within the shell have been plotted on the interaction diagram described earlier above for a typical element within the central circumferential slice The interaction diagram, Figure 15[6], indicates that load effects are dominated by flexure rather than axial compression and so some degree of overload is acceptable.

It is also apparent that at times significant tension stresses are developed in the shell and at the footing. This is the consequence of the linear elastic analysis adopted for the solution. In fact as tension loads developed exceed the gravity loads uplift of the footing may be expected with the consequent relief of such loads. Similarly if in the remainder of the arch significant tension stresses were to develop then tension cracking could be expected in the concrete with the consequent relief of such loads. The tension stresses thus depicted in this figure are thus considered to be fictitious.

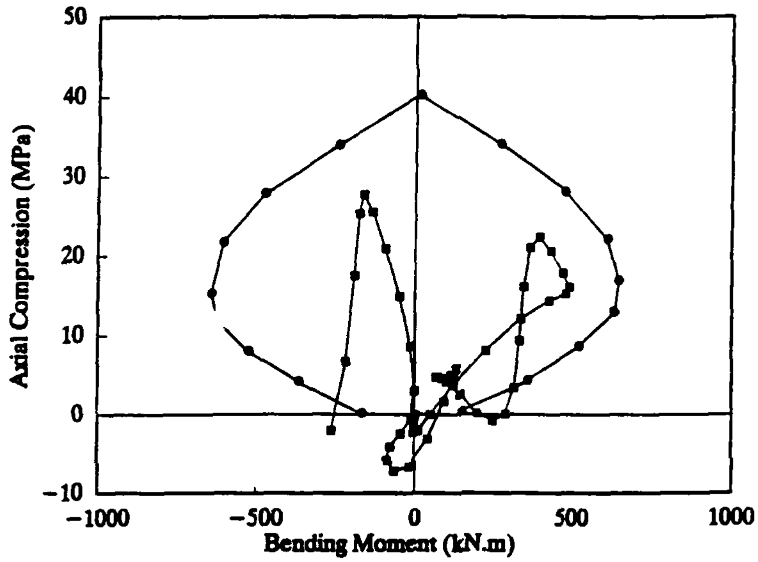

Figure 15. Typical Interaction Diagram Plot for Element

The results obtained for this element, and others not shown here suggest that the real structure, in places, approached and in some areas exceeded the bounds of the interaction diagram. As the overstress generally occured in areas of relatively low compressive stress, the most likely result is some concrete cracking and yielding of reinforcement. Whilst the results do not suggest any significant risk of collapse they do suggest that at some points significant cracking may have occurred.

In view of the absence of any perceptible permanent deformation in the structure it is considered that the results tend to err on the side of conservatism.

6 Note that only blast load induced stresses are plotted in this figure. Gravity induced loads result in an axial stress of the order of 2 MPa, with only minor bending moments, and although these should be included in the load check it is apparent that they will only have a minor effect on the outcome.

5.5 COMPARISON OF ANALYTICAL AND INSTRUMENTAL RESULTS

The discrepancy between the analytical and predicted response, whilst not unexpected, is a cause for a re-examination of a number of issues and assumptions.

(a) Boundary Conditions assumed for the arch

The analysis adopted rotational springs at the arch footing line. The rotational stiffness was calculated using half space theory for the actual footing width and assumed the soil properties determined by test. Previous analyses suggest that any reasonable variation in the end fixity conditions should not affect the results significantly.

Linear elastic boundary elements were also used to provide vertical and horizontal restraint to the footing. Such springs imply a capacity to resist uplift which in practice cannot occur i.e. tension between soil and footing cannot be sustained.

(b) Parameters assumed for the soil cover to the arch

Although the soil properties were formally determined, the analysis transformed this data into equivalent properties for a linear elastic isotropic medium. Whether a moderately loose soil subjected to severe transient loads can be effectively modelled by a linear elastic model is open to question.

(c) Anisotropy of the Concrete Section

As noted earlier the SPANTECH sheeting, because of its deep rib, results in a section with quite different properties in the longitudinal and transverse direction. Moreover the stiffness in the transverse direction is dependent on the sense of flexure induced. If bending actions result in transverse tension stresses in the bottom face then only a portion of concrete shell is effective. When bending actions result in compressive stresses - as the ribs are not in ideal contact some reduction in the effective stiffness can be expected.

(d) Tension in Concrete Shell

The analysis predicts significant tension stresses in the model. Tension stresses beyond say, 4 to 8 MPa, cannot be resisted by the concrete - with the result that some cracking is likely which will thereby reduce the tension stresses and also material stiffness to zero. This effect cannot be modelled by a linear elastic analysis and so the analytical model is likely to be stiffer than the real system.

In summary there are a number of aspects that could lead to a more accurate prediction, however most would require a considerably more detailed model and a program with the capacity to handle the non-linear aspects of the problem. Such analyses would consume substantially greater computer resources than already expended.

6. CONCLUSIONS

As a result of this investigation, the following conclusions are drawn,

1. The receptor structure withstood the blast environment generated by the detonation of 75,000 kg in a 13 m span SPANTECH receptor sited at D3 distance with minimal damage and is therefore considered suitable as an hardened ESH.

2. The blast environment generated in the far field suggests that a complete detonation was achieved. However the blast loads measured in the near field are significantly lower than might be expected based on the predictions on the UK ESTC criteria. They are however comparable to the values experienced in the May 90 trial.

3. The better than expected performance of the receptor structures is considered to be partly due to the 'low' blast loads applied and also partly due to the fact that the arch concrete strength significantly exceeded the specified level.

4. Analysis of large span receptor suggests a level of response broadly in agreement with the experimentally determined values. Although it was often difficult to reconcile the predicted variation of displacement with time with the measured response, the predicted peak total displacement of the order of 50 mm was very similar to that determined from the LVDT records. The predicted response for the imposed loads thus confirms that the arch would, at most, experience only minor distress.

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CONWEP, Conventional Weapons Analysis

ASSESSMENT OF HAZARDOUS AREAS WHEN STORING HD 1.1 AMMUNITION IN FRENCH "IGLOO TYPE" MAGAZINE.

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ABSTRACT :

The French Army presently stores its ammunition inside" Igloo type" magazines, the unit capacity of which is 60 metric tons. Within the framework of pyrotechnical safety, the S.T.B.F.T. was asked by the Army Staff to determine by tests the extent of the hazardous areas related to this type of storage and to compare the results to the quantity distances (Q - D) selected in the French regulations.

The first phase of this test campaign, the subject of this paper, is only concerned with the assessment of Q - D related to blast effects (HD 1.1).

Twenty-one scaled tests (1 : 3) were performed in earth covered steel arch igloos. Different arrangements were tested in order to determine the influence of various parameters.

During the whole campaign, more than 300 blast pressure data were recorded, which enables to make an accurate comparison with the French regular Q - D and to add useful information to the numerous tests already performed in this area by other countries.

I - INTRODUCTION :

As far as the pyrotechnical safety is concerned, French regulation specifications originate from the NATO AC 258 working group.

In particular, this group has determined the Q - D reductions to apply in case of explosion of HD 1.1 ammunition in an igloo type magazine.

Numerous tests and studies have already been performed in several countries, particularly in the United States and in the United Kingdom, in order to limit the extent of hazardous areas in that case.

The methodology adopted by the S.T.B.F.T. during these experiments is different in so far as the same tests were repeated several times in order to gather a lot of coherent data.

Moreover, some complementary tests were performed in particular conditions in order to determine the influence of various factors such as the loading rate and the environment near the donor.

Before giving the results, it seems important to recall briefly some specific points included in the French pyrotechnical safety regulations.

SITING RULES FOR FACILITIES

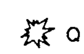
HAZARDOUS ZONES	PYROTECHNICAL ACCIDENT PROBABILITIES				
	P_1	P_2	P_3	P_4	P_5
Z1	a_0	a_0	a_0	a_0	a_0
Z2	a_1 a_2	a_1 a_2	a_1	a_1	a_1
Z3	$a_1 b_1 c_1$ a_2 a_3	$a_1 b_1 c_1$ a_2	a_1 a_2	a_1	a_1
Z4	$a_1 b_1 c_1$ $a_2 b_2 c_2$ a_3	$a_1 b_1 c_1$ $a_2 b_2 c_2$ a_3	$a_1 b_1 c_1$ a_2	a_1 a_2	a
Z5	$a_1 b_1 c_1$ $a_2 b_2 c_2$ $a_3 b_3 c_3$	$a_1 b_1 c_1$ $a_2 b_2 c_2$ $a_3 b_3 c_3$	$a_1 b_1 c_1$ $a_2 b_2 c_2$ $a_3 b_3 c_3$	$a_1 b_1 c_1$ $a_2 b_2 c_2$ $a_3 b_3 c_3$	$a_1 b_1 c_1$ $a_2 b_2 c_2$ $a_3 b_3$

Example

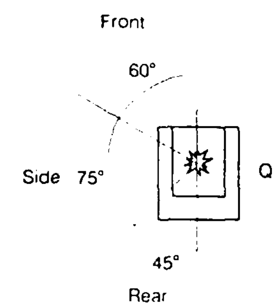
Ammunition storage under igloo => P1
Inhabited building => category C3
=> authorized siting zone Z5

Table 1

HAZARD ZONES 1.1
FRENCH REGULATIONS



In the open



Under igloo

Zi	P (bar)	Scaled distance (m/ kg $^{1/3}$)			
		In the open	Front	Side	Rear
Z1	> 0.6				
		5	5	5	5
Z2	0.3< P<0.6				
		8	8	8	8
Z3	0.1< P<0.3				
		15	15	15	12
Z4	0.05< P<0.1				
		22	22	18	14
Z5					

Table 2

II - SOME SPECIFIC ASPECTS OF THE FRENCH REGULATIONS :

The different installations to be protected against the effects of accidental explosion inside a pyrotechnical site are divided into three large categories, depending on their type and location in relation to the site:

- buildings or facilities inside the pyrotechnical site : category a.
- external public traffic routes : category b.
- buildings or facilities outside the pyrotechnical site : category c.

Table 1 indicates the allowable hazard level that is the potential location of the various categories of facilities mentioned above in every hazard zone defined as follows by :

- the pyrotechnical probability accident level selected,
- the category of building or facility considered.

Table 2 determines the extent of hazard zones HD 1.1 in case of open air burst or inside igloo burst as well as the incident pressure level expected at the boundaries of each zone.

These scaled distances are the prescriptive figures to which the experimental data have been compared.

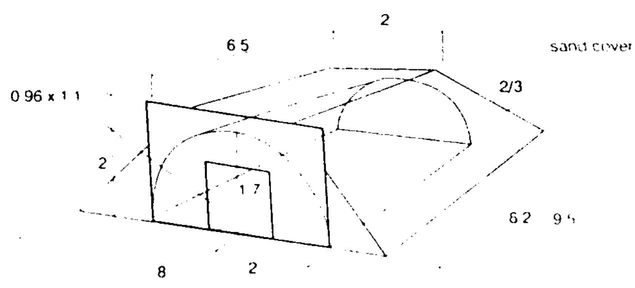
In spite of some specific aspects, the French selected Q - D for free air burst(8 $Q^{1/3}$ - 15 $Q^{1/3}$ and 22 $Q^{1/3}$) are roughly in agreement with Explosive Workshop, Public Traffic Route and Inhabited Building Distances (EWD, PTRD, IBD) mentioned in the NATO regulations.

III - TRIALS SPECIFICATION :

All tests were carried out at 1:3 scale.

31 - Donor characteristics :

During the whole campaign, only one type of donor was used. It was a metal arch sand covered structure, the main characteristics of which can be seen in figure 1. The size of the donor and its sand mound were reduced to 1:3 scale compared with the actual igloo containing 60 metric tons, which can be built with metal or reinforced concrete.



	Scale	Q kg	Loading kg/m3 density	Aspect w/l ratio	Details
L W	1/3	2900	87	0 3	Single bay steel arch igloo e=10mm H x W x L 1 7 x 4 x 6 2m V= 33 1m³ Minimal thickness of sand (apex) 0 3m
		2200	66		

Fig 1

32 - Configuration of tests :

(Table 3)

22 tests were performed, 21 were selected. One of them was not taken into account because of incoherent data.The location of the donor igloo was modified for every test.

Most of explosive trials were conducted under isolated igloos.However, 6 trials were carried out under igloos which were partially or totally surrounded by sand mounds simulating adjacent igloos in order to determine their potential influence on the extent of the first hazard zones in the vicinity of the donor.

In these cases, the distances between the donor and its neighbors were fixed to 0.5 $Q^{1/3}$ side to side and 0.8 $Q^{1/3}$ rear to front according regulation specifications.

33 - Explosive charges involved :

According to the available stocks two types of ammunition were used for the composition of 2.2 ton charges which represented 60 metric tons full size .

- Charge n° 1 : composed with 164 snake demolition M3 cartridges (13.5 kg TNT equivalency per cartridge).
- Charge n° 2 : composed with 44 Benoto torpedoes (50 kg TNT equivalency per torpedo).

In fact, the TNT equivalent weight of the American ammunition had been underestimated. Specific tests revealed thar the real TNT equivalent weight of a cartridge was about 17.5 kg.

Finally, the two types of charge used represented respectively 2.2 tons (60 tons full size) and 2.9 tons (78 tons full size).

These orthorombic shape charges were placed at the center of the donor and were ignited in two points on the opposite of the headwall.

SCOPE OF THE TESTS

Experimental set-up	Charge weight (Tons)	Quantity of tests	Quantity of reliable pressure data
DONOR separate	2.9	13	191
	2.2	2	47
DONOR partially surrounded	2.9	4	66
DONOR surrounded	2.9	2	34
	TOTAL	21	338

Table 3

LOCATION SCHEMES FOR PRESSURE GAGES

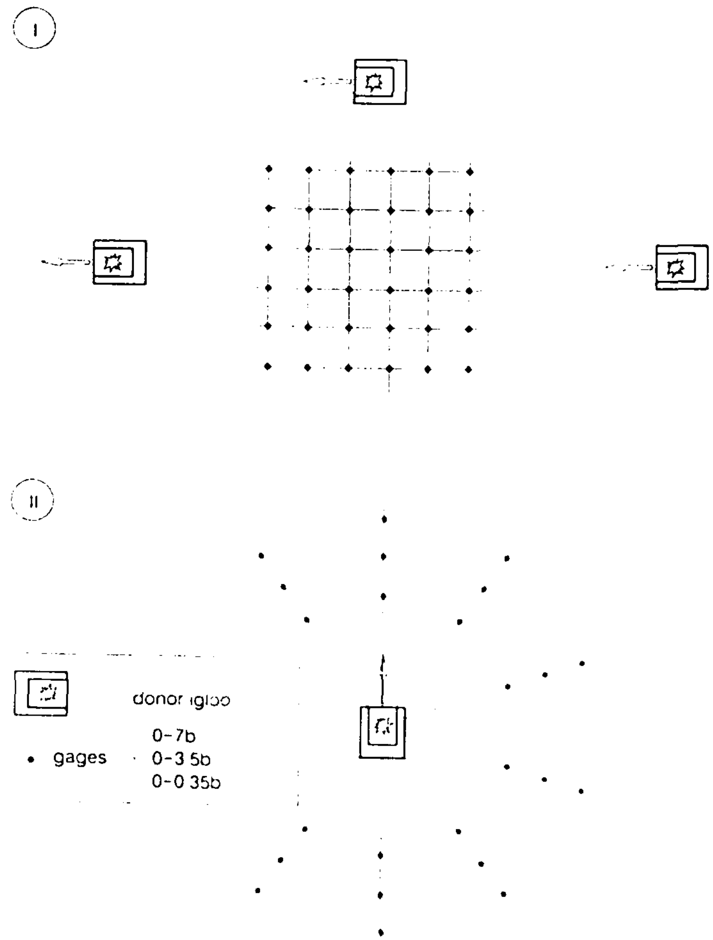


Fig 2

34 - Measurements of blast parameters :

- Pressure :

The pressure measurements were recorded by various range piezoelectric gages depending on their situation away from the donor.

- 0 - 7 bar (0 - 100 psi)
- 0 - 3.5 bar (0 - 50 psi)
- 0 - 0.35 bar (0 - 5 psi)

These gages were located according to different lay-out schemes (fig. 2).

At the beginning, a fixed grid was placed and the data recorded in the different directions were achieved by the donor displacement.

Then in order to outline the isobaric plot 0.05 b the gages were placed radially.

- Impulses :

As the French regulations do not explicitly refer to impulse levels expected at the different hazard zone boundaries, these ones were not considered.

35 - Additional surveys :

The whole tests were covered by high speed and video cameras.

Aerial surveys were performed in order to investigate the shape and the size of the craters.

Finally the location of some debris of the donor which could be easily identified was surveyed, in particular the initial sheet of the donor rear and front walls.

IV - RESULTS PRESENTATION :

For each direction considered, the recorded values were plotted on log-log graphs including the Kingery curve and the step fonction which corresponds to the regular Q - D specifications.

Three series of curves were plotted :

- 1st series : 2.2 metric ton charges.
- 2nd series : 2.9 metric ton charges.

In the 3rd series the curves of 2.2 and 2.9 ton charges were gathered.

In order to get a clear picture only the 3rd series of curves is shown in figures 3a - 4a - 5a. The mean curves derived from the distributed points may be equated by :

- front : $p = 5.82\ x^{-1.64}$
- side : $p = 5.31\ x^{-1.63}$
- rear : $p = 4.03\ x^{-1.55}$

with : p expressed in bar (10^2 kPa)

x : scaled distance expressed in $m/kg^{1/3}$.

The experimental Q - D values have been derived from these equations for pressure levels applied at the hazard zone boundaries and compared with Q - D values mentioned in the French regulations (fig. 3b - 4b - 5b).

Simultaneously with these experimental mean values, maximal values corresponding to the envelope curves were determined (Table 4). In order to be conservative while taking into account the scatter of results it seemed to be suitable to neglect 5 % of the highest pressure data.

Finally these experimental values selected were compared to the regular Q - D

- for under igloo bursts (table 6 + fig 6).
- for open air bursts (table 7 + fig 7)

V - INTERPRETATION OF RESULTS :

51 - Influence of various factors :

* Loading rate of the donor

Studies led in the framework of the AC 258 working group have tried to determine the influence of this parameter on the quantity distances to be considered.

The two loading rates tested during this campaign, 66 kg/m^3 and 87 kg/m^3 did not reveal a substantial difference in the quantity distance values experimentally obtained. This observation has enabled to gather the results of both explosive charges tested in the same group.

* Donor environment

This factor has no significant influence for scaled distances higher than 5 $Q^{1/3}$. At short range, the igloos in the neighborhood of the donor seem to alter the blast pressure level within a range of about 20 %. This increase or decrease depends on the measure point in relation with the donor.

Nevertheless, this 20 % variation should not be overrated since an important scatter of results is always observed at short range however cautious one may have been to perform tests in simil:~ conditions.

52 - Comparison with Q - D regular values :

Generally, the whole experimental results seem to be fairly coherent if we consider the relative positions of the mean values in relation with the Kingery curve.

Morever, for a given pressure level the highest experimental Q - D values are always found in the front direction while the lowest are in the rear one.

When these values are compared with the regular onesin case of accidental explosion under igloo it must be noted that :

- on the front : the experimental results are always lower than the prescriptive values (about 7 %). This can be explained by the fact that, for this direction regular Q - D are the same for open air and under igloo bursts.
- on the contrary, as far as the side and mainly rear directions are concerned the reductions prescribed in the regulations seem too high : for example on the rear face the experimental value for IBD exceeds the regular value by more than 20 % (17 $Q^{1/3}$ instead of 14 $Q^{1/3}$).

	Z1	Z2	Z3	Z4	Z5
P(bar)	0 6	0 3	0 1	0 05	

FRONT

	Z1	Z2	Z3	Z4	Z5
Mean value (1)	4	6 1	11 9	19 7	
Maximum value (2)	4 7	8 9	15 5	22 5	
Selected value (3)	4.5	8	14	20 5	

SIDE

	Z1	Z2	Z3	Z4	Z5
Mean value (1)	3 8	5 9	11 9	17 4	
Maximum value (2)	4 2	7 5	15 2	20	
Selected value (3)	4 1	6 6	13 5	18	

REAR

	Z1	Z2	Z3	Z4	Z5
Mean value (1)	3 4	5 3	10 8	15 8	
Maximum value (2)	3 6	6 2	13 6	18 5	
Selected value (3)	3 5	5 9	13 1	17	

(1) Regression curve

(2) Envelope curve

(3) The 5% most extreme data points not considered

Table 4

This experiment has revealed a comparatively small distorsion between the front and the rear Q - Ds :

$$\frac{\text{Q - D Front}}{\text{Q - D Rear}} = 1.2 \quad \text{(average value).}$$

We may infer that the igloo metal type and its arch shape have slighty reduced the confinement level of the explosion. This could partially explain the relatively high rate of energy dissipated in the rear direction.

VI - CONCLUSION :

Certainly, these scale tests performed in metal structures have specific configurations.

Nevertheless, these series of trials give additional information to the whole studies which have been conducted in several countries for the past 20 years in order to define more accurately the extent of hazard zones resulting from accidental explosion in a storage igloo.

Other types of hazard are still to be assessed, mainly those which are caused by fragments and debris . This question should be examined in future trials.

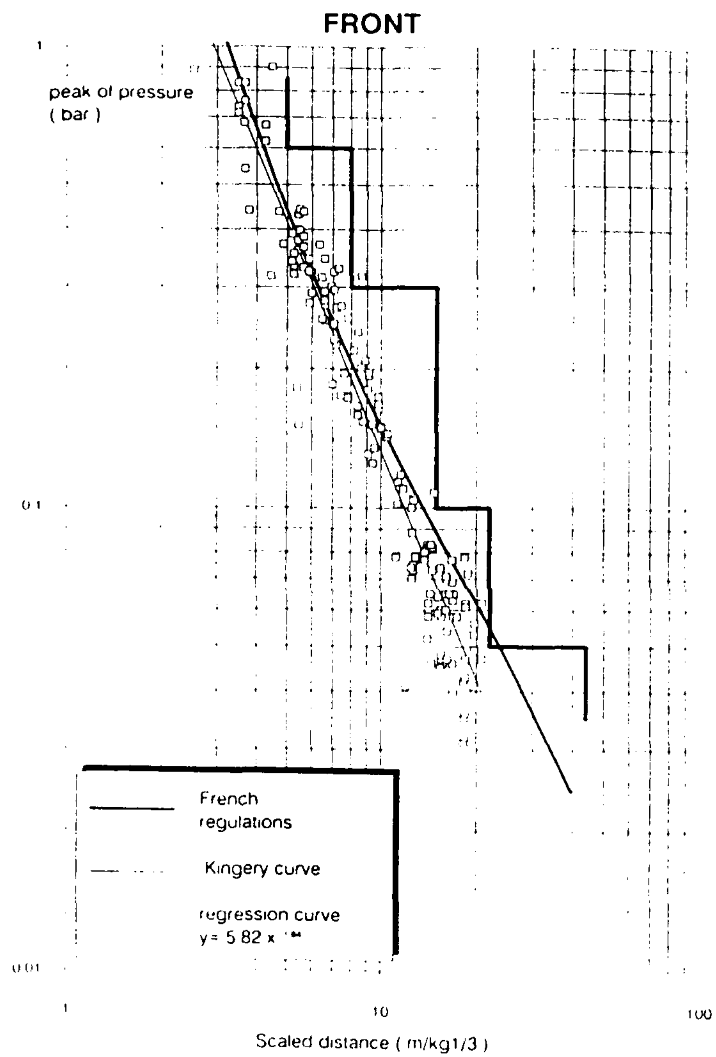

FRONT
peak of pressure
(bar)
1
0 1
0 01
1
10
100
Scaled distance (m/kg1/3)
French regulations
Kingery curve
regression curve
y= 5 82 x

Fig 3a

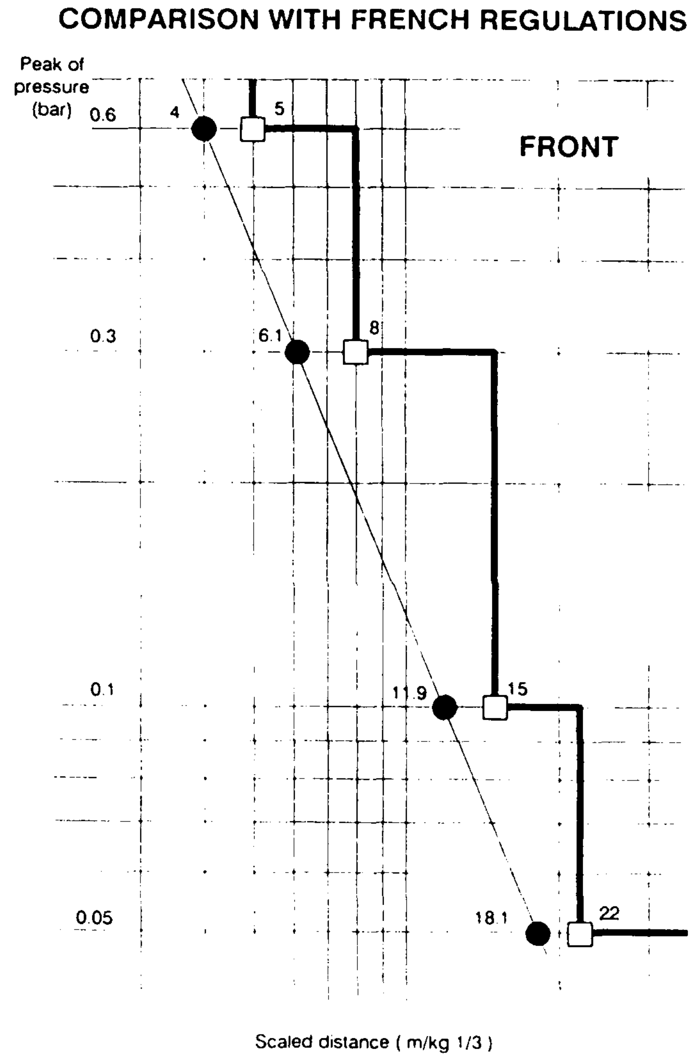
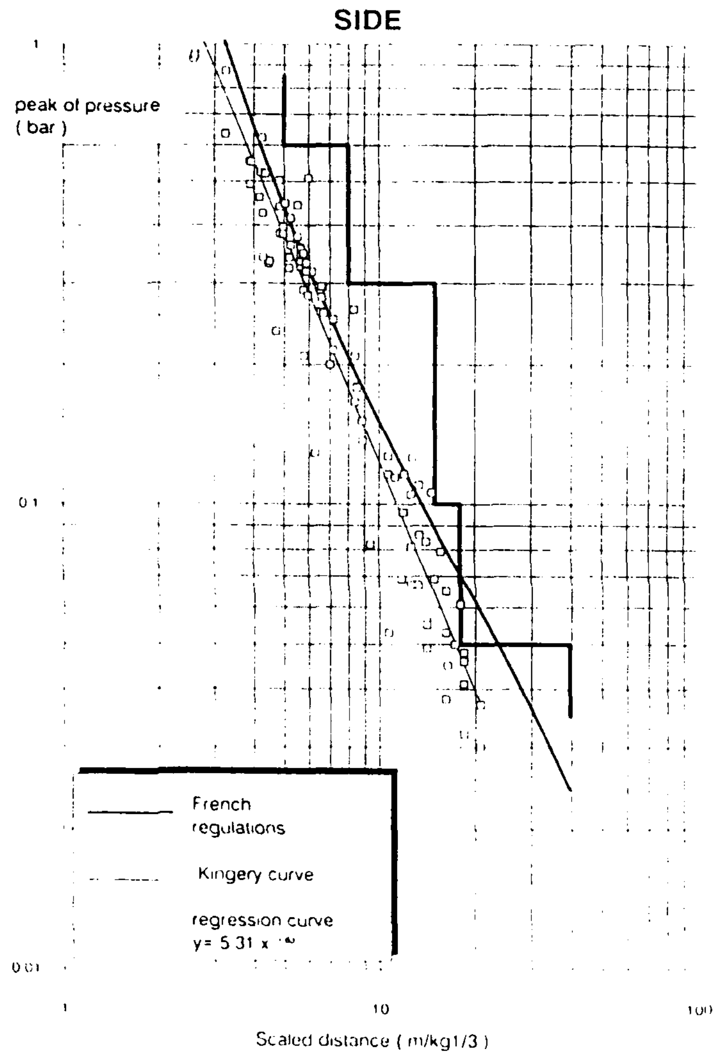
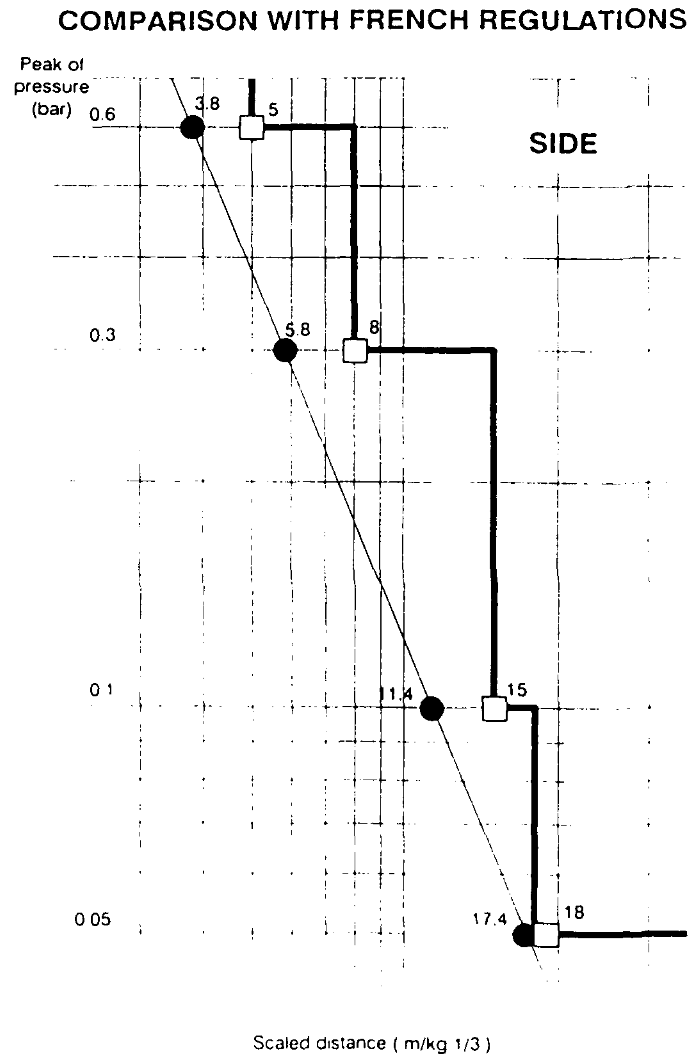

COMPARISON WITH FRENCH REGULATIONS
FRONT
Peak of pressure (bar)
0.6
0.3
0.1
0.05
4
5
6.1
8
11.9
15
18.1
22
Scaled distance (m/kg 1/3)

Fig 3b



SIDE
peak of pressure
(bar)
1
0.1
0.01
1
10
100
Scaled distance (m/kg1/3)
French
regulations
Kingery curve
regression curve
y= 5.31 x

Fig 4a



COMPARISON WITH FRENCH REGULATIONS
SIDE
Peak of
pressure
(bar)
0.6
0.3
0.1
0.05
3.8
5
5.8
8
11.4
15
17.4
18
Scaled distance (m/kg 1/3)

Fig 4b

COMPARISON WITH FRENCH REGULATIONS

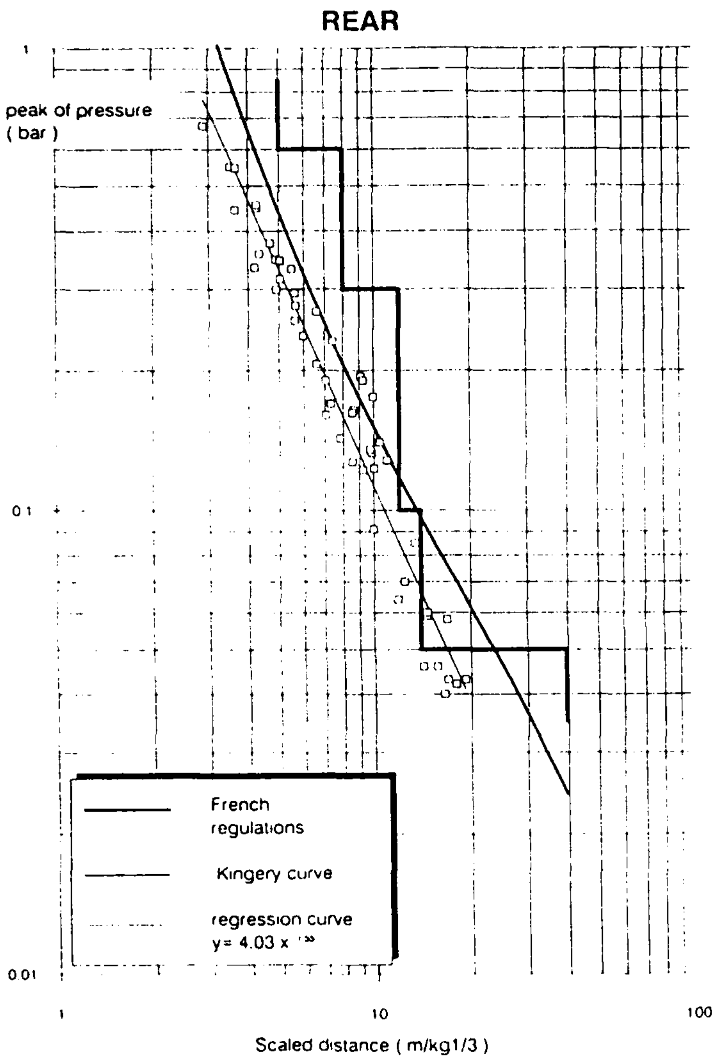


Fig 5a

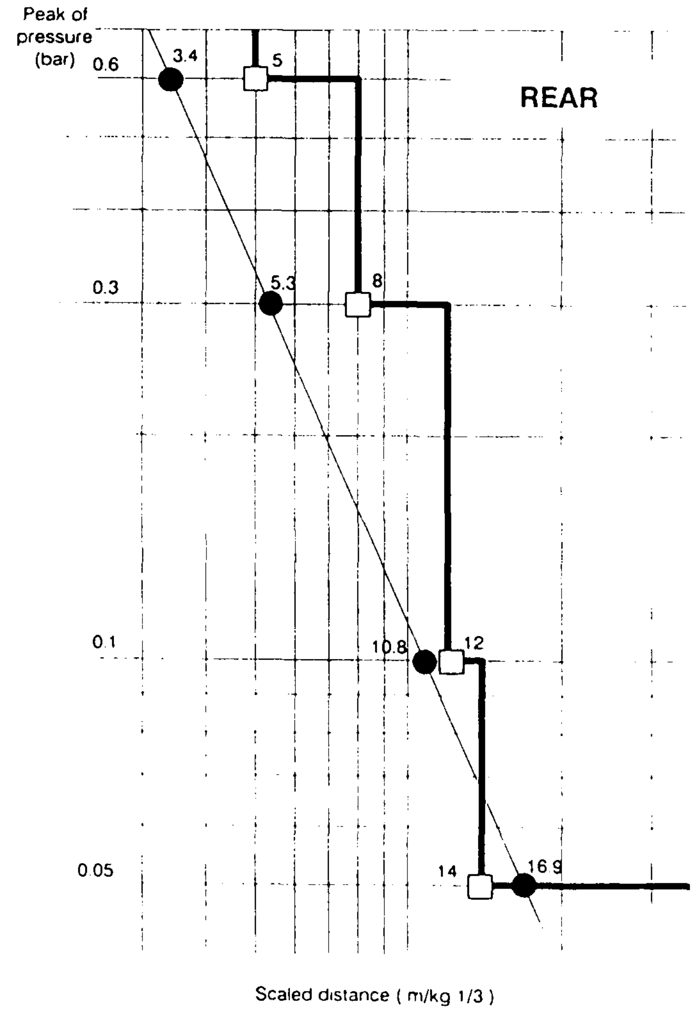


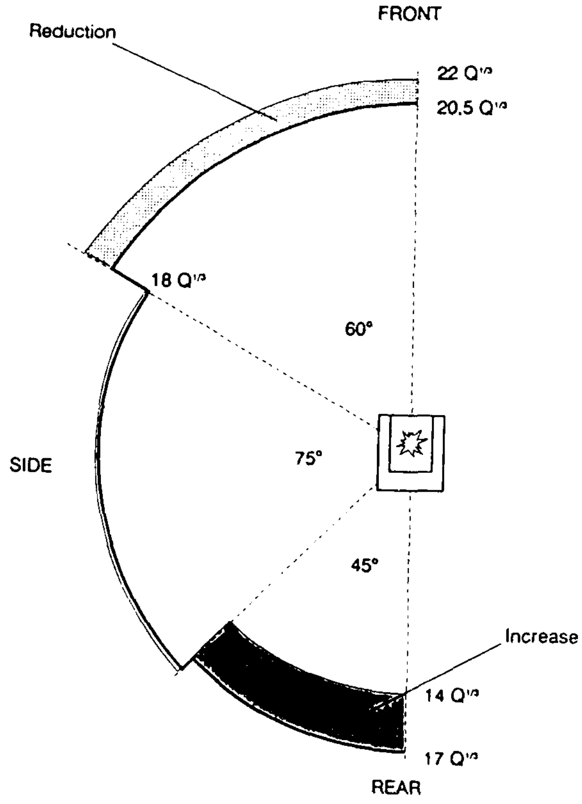
Fig 5b

COMPARISON WITH Q–D REGULAR VALUES
(Under Igloo)

	Z1	Z2	Z3	Z4	Z5
P (bar)	0 6	0 3	0 1	0 05	
FRONT					
Regulations value	5	8	15	22	
Trials Result	4 5	8	14	20 5	
% Reduction (−) / Increasing (+)	- 10%	0%	- 7 %	- 7 %	
SIDE					
Regulations Value	5	8	15	18	
Trials result	4 1	6 6	13 5	18	
% Reduction (−) / Increasing (+)	- 18 %	- 17 %	- 10 %	0 %	
REAR					
Regulations value	5	8	12	14	
Trials result	3 5	5 9	13 1	17	
% Reduction (−) / Increasing (+)	- 30 %	- 26 %	+ 9 %	+ 21 %	

Table 6

COMPARED SCALED RANGE FOR IBD



Regular values : —— Under igloo

Trials result : ——

Fig 6

COMPARISON WITH Q–D REGULAR VALUES
(In the open air)

ZONE	Z1		Z2		Z3		Z4		Z5
P(bar)		0.6		0.3		0.1		0.05	
Regulations Value		5		8		15		22	

FRONT

Trials result		4.5		8		14		20.5	
% reduction (-)		- 10 %		0 %		- 7%		- 7%	

SIDE

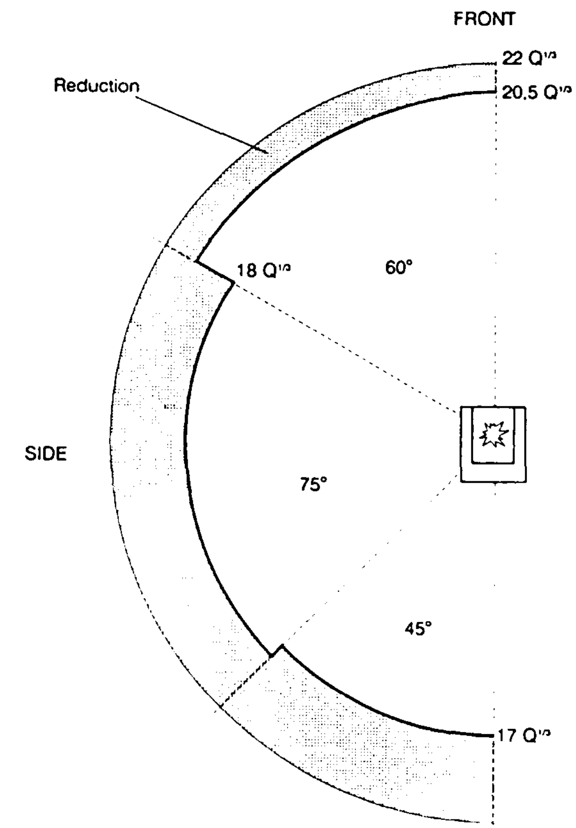
Trials result		4.1		6.6		13.5		18	
% reduction (-)		- 18 %		- 17 %		- 10 %		- 18 %	

REAR

Trials result		3.5		5.9		13.1		17	
% reduction (-)		- 30 %		- 26 %		- 12 %		- 22 %	

Table 7

COMPARED SCALED RANGE FOR IBD



Regular values : In the open air

Trials result :

Fig 7

Calculation of Hazardous Soil Debris Throw Distances Around Earth Covered Magazines

by

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1.0 Introduction

Earth-covered magazines must be sited so that personnel in nearby inhabited areas are protected from hazardous blast pressures, fragments, and thermal loads. DoD 6055.9-STD "Ammunitions and Explosives Safety Standards"[1] gives criteria for determining the distance required to provide such protection. For charge weights less than 45,000 lbs of Class/Division 1.1 explosive, the default distance required in DoD 6055.9 to provide protection from hazardous fragments controls the required siting distance between an earth-covered magazine and an inhabited building. For lower explosive weights (charge weights less than 6000 lbs), the default fragment protection distance controls over the required blast and thermal protection distance by a factor of two or more.

The default fragment protection distances are not intended to directly account for the many variables that affect fragment and structural debris throw from earth covered magazines. Rather, they are intended to be very easy to apply and to provide an acceptable amount of protection for a wide range of explosive weights. As a result the default distances can be very conservative, especially for lower explosive amounts. DoD 6055.9 does allow for a reduced fragment protection distance, and therefore a lesser siting distance, if it can be shown by analysis that the hazardous fragments and debris from structural elements of the facility do not present a hazard (no more than one fragment per 600 ft^2) beyond the reduced distance and if the required blast and thermal protection are provided. Calculated fragment protection distances are typically less than the default distance for low explosive weights and for these cases, usually result in a reduced siting distance. Therefore, there has been considerable interest in calculating the fragment protection distance around storage and testing sites containing relatively low explosive weights. An example of this is a recent program

at Southwest Research Institute (SwRI) where a detailed test program was conducted to investigate the fragmentation of building walls under explosive loading and wall debris throw so that a model could be developed, based largely on the test data, that predicts the maximum hazardous structural debris throw distance from a building.[2] This program, which was funded by the U.S. Department of Energy, addressed only conventionally constructed buildings (without earth cover) containing a maximum of 250 lbs of TNT.

For the case of earth covered magazines, the distance soil debris from the earth cover is thrown must be considered in any analysis of the required fragment protection distance. All fragments and debris with 58 ft-lbs of kinetic energy, or more, are considered hazardous by DoD 6055.9. Since a cubic soil fragment weighing just 0.28 lbs will have 58 ft-lbs of energy upon impact with its free-fall velocity, an explosion in an earth covered magazine will produce many hazardous soil debris, or dirt clods. In a recent project for the LTV Missiles and Electronics Group, a method was developed and used by SwRI to calculate the maximum distance soil debris are throw by an explosion in an earth covered magazine. In this paper this method is discussed and compared against limited full scale data. The required fragment protection distances calculated around two earth covered magazines at the LTV testing site with this method are also presented.

2.0 General Discussion of the Problem

The method presented in this paper for calculating soil debris dispersion is based on the same three steps that are used to predict building debris dispersion in Reference 2. These three steps are; 1) calculate the total impulse (shock plus quasistatic) applied to the building walls and roof, 2) using the impulse and the building material type as inputs, calculate the initial launch conditions of the building debris (that is, the debris initial velocities, launch angles, masses, and drag characteristics), and 3) using the initial launch conditions as inputs, calculate the distances traveled by the debris with a computer code that models the drag and gravity forces acting on the debris during flight.

These steps are used as a guide to develop the method for calculating soil debris dispersion because they make up a general theoretical approach that has been used successfully, along with test data, to predict building debris dispersion.[2] These steps are also similar in concept to a previous method which was developed to predict the response of the roof of earth covered magazines to an internal explosion and was verified in a scaled experimental test program.[3] The application of these general steps to the case of calculating soil debris throw from a typical earth covered magazine is more complex in some respects than the case of calculating building debris throw in Reference 2. The additional complexities which must be considered for the case of soil debris throw are discussed below.

1) The shock impulse on the magazine walls includes impulse from repeated shock wave reflections off each reflecting surface in the magazine. Because of the typically high loading densities within magazines, and the resulting very high temperature and

pressure environment in the magazine immediately after the explosion, the shock wave reflections will travel much more quickly, and decay more slowly, than they would in a room with a low loading density. Therefore, the methods in TM5-1300[4] and in Reference 2 for calculating shock impulse, which are based on only one shock wave reflection off each reflecting surface, may significantly underestimate the shock impulse affecting debris throw from an earth covered magazine.

2) There is no known available method for predicting the duration of the shock impulse in the magazine taking into account the early time failure of the magazine door and front wall, and subsequent leakage of the shock wave outside the magazine. This issue is important for a typical magazine because of the high loading density discussed above and the resulting long duration shock pressure history.

3) There is no known available method for time-stepping through the venting process that considers simultaneous nonuniform shock impulse and quasistatic impulse acting on the vent panel. The FRANG code,[5] which is an available tool for calculating quasistatic impulse in a room with a vent panel, assumes that all shock impulse is applied prior to the buildup of quasistatic impulse. This is the typical case for rooms with lower loading densities. However, in a typical magazine, it is expected that the shock impulse duration can extend throughout most or all of the quasistatic duration because of the factors discussed in No. 1 above.

4) There is no known computer code for time-stepping through the venting process which considers venting through multiple vent areas which have significantly different mass per unit area. In the magazine venting occurs very quickly through the door, which fails first, and then begins at a slightly later time through the front wall, which fails second, and finally occurs through the roof, which fails before any of the earth covered sides because it has less soil cover. The mass per unit area and the time to initial venting of each of these three vent areas are significantly different from each other. The FRANG code only considers venting through one covered vent area with a given mass per unit area.

5) The manner in which the soil cover breaks up into debris is not well known because the size, initial velocity, and the initial launch angles of soil debris from earth covered magazines subjected to internal explosions have not been measured in experimental programs.

The method described below for calculating soil debris dispersion addresses these problems based on the use of available predictive tools for calculating impulse in the magazine which are modified by engineering judgement to take into account the above-mentioned shortcomings in these methods. It is expected that as more data and improved predictive tools become available, these data and predictive tools can replace some of the current need for engineering judgement.

3.0 Description of the Method Used to Calculate Soil Debris Dispersion

The first step in the procedure for calculating the soil debris dispersion is to calculate the total impulse on the magazine roof and walls that contributes to the initial velocity of the soil debris. The assumption is made that, while spall of the soil can occur, the maximum soil debris velocity is caused by the acceleration of the overall soil mass from the full duration of the blast load, or from the impulse. The calculation of the impulse is subject to the difficulties listed in numbers 1 through 4 above. The shock impulse, which is subject to the difficulties in numbers 1 and 2 above, is calculated on the roof and the frontwall of the magazine in this method with the BLASTINW code.[6] This code is considered the most appropriate available shock impulse prediction tool for the high loading densities typical of storage magazines because it considers repeated shock reflections off each reflecting surface throughout the input time of interest and it predicts the time at which quasistatic pressure begins to load each building surface. A second major assumption in this method is that the duration of the shock impulse is assumed equal to the time up until critical venting of the quasistatic impulse out the frontwall. Critical venting is defined as the condition where the vent panel has moved out a distance such that the vent area around the vent panel is equal to the area of the originally covered vent opening. The assumption here is that the opening created by the movement of the vent panel (front wall of the magazine) up until critical venting provides a sufficient area for the shock waves to vent out, or leak from the magazine and thus cease to reflect within the magazine. Very high shock impulses are calculated (as high as 35 psi-sec) up until the time of critical venting (about 5 to 7 milliseconds after detonation) in magazines with 1000 to 5000 lbs of explosive and loading densities of 0.5 to 1.3 lb/ft^3. As a means of comparison, these impulses are considerably higher than those calculated for the same buildings with the SHOCK computer code,[7] which only considers <u>one</u> reflection off each reflecting surface, that is called out in References 2 and 4 for calculating the shock impulse inside of buildings which typically have loading densities at least an order of magnitude smaller than earth covered magazines. The currently available version of the BLASTINW code only considers rectangular structures. Comparisons performed at Southwest Research Institute[8] between measured shock pressures in cylindrical structures and those calculated by BLASTINW using a circumscribed square cross section showed relatively good agreement. Therefore, the shock impulse in a typical semicircular arch magazine can be approximated using a rectangular structures constructed in this manner. New versions of BLASTINW will consider cylindrical structures.[9] The shock pressure history calculated by the BLASTINW code has not been validated at the high loading densities typical for earth covered magazines.

Quasistatic impulse is calculated with the FRANG[5] computer code. The magazine door is considered as uncovered vent area (since the very high impulses involved overwhelm the door mass and cause the door to be thrown out very quickly) and the front wall is input into the FRANG code as the covered wall area. The calculation of quasistatic impulse is subject to difficulties number 3 and 4 described in the previous section. As an approximate method of dealing with the third difficulty using the FRANG code, a portion of the shock impulse acting on the vent wall up until the time of the critical venting is input into FRANG. This portion of the impulse, which is assumed

by the code to be immediately applied, is chosen so as to cause the vent panel to move out approximately the same distance in the FRANG code as it is actually moved by the gradually applied shock impulse during the time up until critical venting. The BLASTINW output shows the shock impulse on the front wall increases nearly linearly with time. This implies that the average shock impulse (one-half the shock impulse at critical venting) input into the FRANG code, and therefore applied immediately to the covered vent area, will cause approximately the same vent panel movement prior to critical venting as the actual (linearly increasing) shock impulse. The approximate nature of this method is caused primarily by the fact that venting of quasistatic pressure is sensitive to the time history of the vent wall movement prior to critical venting, not just to the overall distance the vent wall moves prior to critical venting. This approximate method requires an iterative approach where, 1) the critical venting time is first assumed, 2) based on this assumed time, the average shock impulse on the headwall calculated with the BLASTINW code up until the assumed critical vent time is input into FRANG, 3) the FRANG code is then run, and 4) the calculated time until critical venting is compared to the assumed value. If the assumed and calculated critical vent times match closely, then the critical vent time, and thus the assumed duration of the relevant shock impulse, is known.

The FRANG output using the above approach predicts that a significant amount of additional quasistatic impulse occurs in the structure after critical venting since it takes some time for venting through the front wall to cause the pressure in the structure to drop to zero. However, the two foot of fill over the roof of the magazine also begins to vent at about the same time critical venting occurs through the front wall. The approximate time required for venting to begin through the roof is determined by calculating the time required for the roof to move through the roof and overlying soil thickness. This time is calculated assuming the roof velocity is equal to the impulse divided by the roof and soil mass, and that impulse builds up linearly prior to critical venting and is constant thereafter. Only the quasistatic impulse from the FRANG code occurring prior to venting through the roof is considered because it is assumed that the quasistatic pressure will drop to zero very quickly after venting through the large roof area begins.

In summary methods have been presented to calculate the shock impulse (with BLASTINW), the shock impulse duration (equal to the time up until critical venting as calculated with FRANG), the quasistatic impulse (with FRANG using a iterative method to apply the correct shock impulse to the vent panel), and quasistatic impulse duration (the time up until venting begins through the roof). This concludes the first, and most complicated, step in the method which is to calculate the total shock and quasistatic impulse affecting soil debris dispersion. The complexity is primarily due to the fact that existing tools for predicting impulse are based on assumptions that are applicable for typical testing and assembly bays but are not thought applicable to magazines with high loading densities and multiple covered vent areas.

The next step is to determine the initial launch conditions of the soil debris which are the debris initial velocity, vertical launch angle, mass, and the drag characteristics. Because of the numerous difficulties involved in assuming even worst case initial launch condition, no attempt is made to define the range of each of the debris initial launch condition values. Therefore only the worst case, or furthest throw distance of the soil debris is considered in this method rather than the distance where a critical density (more than 1 per 600 ft^2) of soil debris occurs. However, since the soil cover is assumed to break into many small clods, it is thought that critical debris densities will probably occur at, or very near, the maximum soil debris throw distance.

The two launch characteristics which affect the calculated debris throw distance most are velocity and launch angle. The total shock plus quasistatic impulse, as calculated using the procedures discussed above, is used to determine the maximum soil debris velocities. All the force in the applied impulse is assumed to accelerate the soil debris and, therefore, the soil debris velocity is equal to the total impulse divided by the mass of the overlying soil and structure. This assumption is considered valid because any strain energy absorbed by the earth magazine, which is designed to support only the surrounding soil loads and not any of the very large internal blast pressures, is negligible compared to the energy applied during an explosion. The worst case launch angles are considered to be a function of the magazine geometry. In arch magazines (such as that shown in Figure 1) soil debris across the cross section is assumed to be launched at the angle normal to the cross section. This assumption is based on an assumed radial expansion of the magazine cross section under the largely uniform internal blast pressures. In rectangular magazines (such as that shown in Figure 2), and out the back of arch magazines, where the backwall and roof meet at right angles, the prevalent launch angles are straight up vertically and straight out horizontally. However, these two cases do not represent worst case launch angles because the vertical throw, which will have high velocity, will not translate a large distance horizontally, while the horizontal soil throw will have a relatively low velocity because of the large mass of soil backing the walls. Soil thrown at a forty-five degree launch angle, but subject to a reduced impulse (less than the total calculated impulse acting on the roof and walls), is considered the worst case launch angle for this case. These two magazine cross sections, a semicircular cross section and a rectangular cross section, are discussed separately in more detail below.

For the case of the semicircular cross section, the mass of the surrounding soil, and thus its initial velocity, varies around the radius of the cross section as Figure 1 shows. Assuming that soil debris launch angles are equal to the direction of the unit normal off the cross section, the soil near the crown with the least depth, and therefore the largest initial launch velocity, will have a very high launch angle (near 90 degrees). This launch angle precludes a large debris throw distance. At the other extreme is soil over the 45 degree radial, which lies on the optimum launch angle but has more overlying soil and therefore, a relatively low launch velocity. In order to simplify the method, two launch angles are assumed (based on trial and error calculations with a number of possible angles) to represent possible worst case conditions for soil debris throw; 1) a 70 degree launch angle where a very high velocity will be combined with a steeper launch angle, and 2) a 45 degree launch angle where more soil mass, and thus a much lower launch velocity, is combined

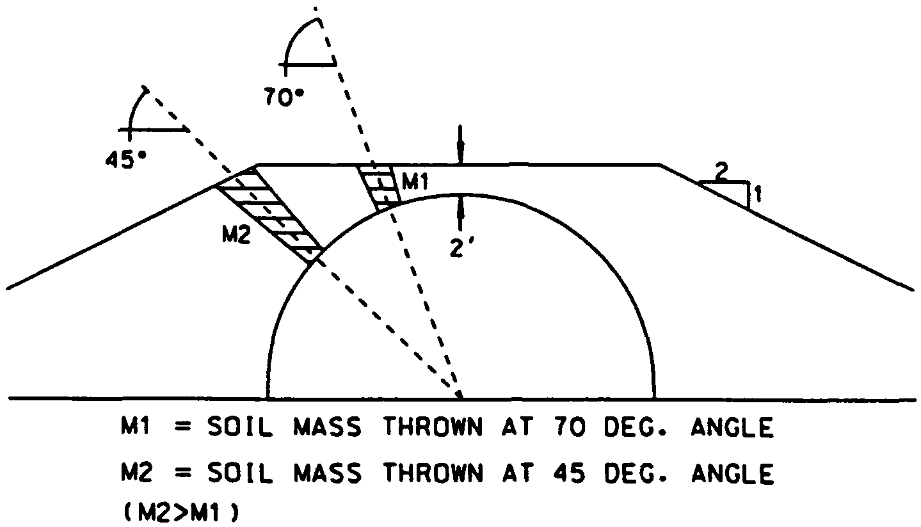

Figure 1. Assumed Soil Masses Thrown at Critical launch Angles (45° and 70°) in Plane of a Circular Area Magazine Cross Section

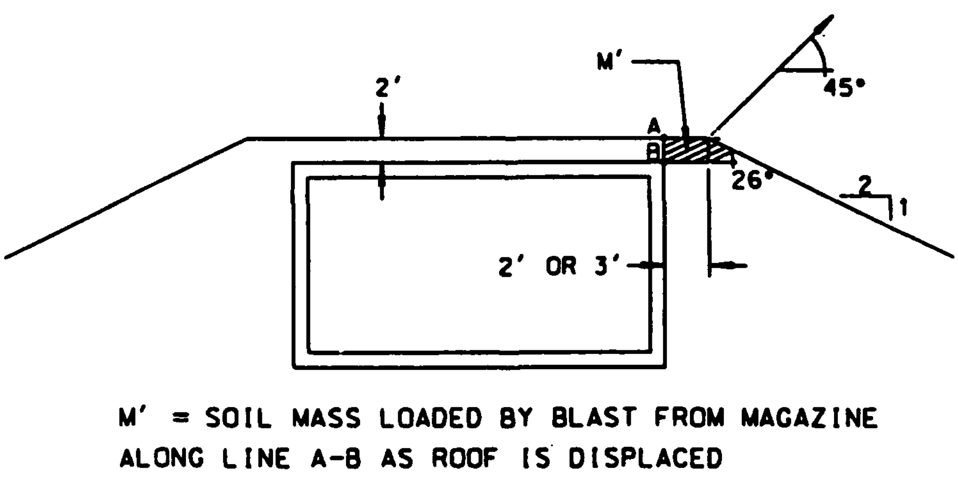

Figure 2. Assumed Soil Mass Thrown at 45° Launch Angle in Plane of a Rectangular Box Magazine

with a near optimal launch angle. The furthest throw distance calculated for these two discrete soil masses, which are illustrated in Figure 1, is assumed to be the hazardous soil debris throw distance. For typical arch magazines, the magazine backwall and roof usually meet at a right angle. Therefore soil debris out the back is analyzed in a similar manner as soil debris throw from a rectangular magazine discussed below.

In a rectangular structure, where the roof and wall meet at a right angle, most of the soil debris will be thrown straight upwards because the roof, which has much less earth cover than the walls, will fail first and be thrown primarily upward. However, the launch angle considered worst case for soil debris throw distance in this method is a 45 degree angle out the top corners of the magazine as mentioned previously. The area of the assumed soil block which is thrown the maximum distance is shown in Figure 2. However, this soil mass is not directly loaded by the impulse in the structure. It is loaded only as the roof moves upward and exposes it to internal blast pressures. Since the shock impulse increases approximately linearly with time, the shock pressure in the magazine (which causes the major part of the total calculated impulse) acting on the structure and surrounding soil can be assumed to be largely constant neglecting the very short duration transients that occur. For the assumption of a largely constant internal pressure, the impulse acting on the soil mass assumed to be thrown the furthest distance, which is surface A-B in Figure 2, can be calculated as one third of the total impulse in the structure.[10] Therefore, soil debris velocity of this critical soil mass is calculated as one third the impulse on the roof divided by the soil mass (the shaded area in Figure 2) and the launch angle is assumed to be forty-five degrees.

The final required soil debris launch characteristics are the debris mass and drag characteristics. The primarily cohesive soil fill over the magazine is assume to break into many clods with widely varying mass. Therefore the size and drag characteristics of the soil debris are very difficult to predict theoretically. Fortunately, the throw distance is not very sensitive to these two launch characteristics. It is known from testing of buried explosive charges in clay that typically chunky soil debris is produced rather than "pancake" shaped debris. It is also known that the maximum size debris near the outer limits of soil dispersion from large cratering experiments weigh approximately one-thousandth the charge weight.[11] The charge weights stored in earth covered magazines vary considerably but, assuming that they vary between 1000 and 10000 lbs, the largest soil debris weights would be between one and ten pounds. Based on these limited guidelines a "typical" debris weight of one pound is assumed for the single fragment throw distance, or trajectory calculations, and it is assumed that the fragments are cubic.

Finally, in the last step in the soil debris dispersion calculation procedure, the MUDEMIMP code[12] (or a similar trajectory code) is used to calculate the throw distance for each worst case (or possible worst case) soil fragment under consideration. The maximum debris velocity, calculated from the total impulse and soil mass as discussed above, the assumed launch angle, the soil fragment mass (1 pound), and the drag coefficient for the assumed cubic shape are input into the trajectory code and a distance to first impact is calculated. No roll of the soil debris after first impact is assumed since it will the soil is assumed to deform substantially upon impact. It is assumed that

no structural debris, which is buried under at least two feet of soil and will have similar or less severe initial launch angle and velocity, will be thrown further out the soil covered sides of the magazine than the calculated maximum soil debris throw distance. Limited test data shows this to be generally true for standard corrugated arch magazines.[13]

No procedure is developed for calculating soil debris throw out the front of the magazine since structural debris throw from the headwall and door is assumed to control the hazardous fragment distance in this direction.

The best way to gain confidence in this procedure is to compare it to data. This is discussed next.

4.0 Comparison of Analysis Procedure for Soil Debris Dispersion Around Earth Covered Magazines to Data

Data from the test report in Reference 13 (tests on standard earth covered igloos conducted at Naval Ordnance Test Station in the early 1960's) was used to judge the adequacy of the procedure discussed above. Seven full scale tests are described in this report in which several thousand pounds of explosive (equivalent TNT weights ranging from 1275 pounds to 100,000 pounds) were detonated in standard steel arch earth covered magazines. Table 1 shows the charge weights, loading densities, and reported soil debris throw (for the tests where this was reported) for the seven tests. The tests were conducted to verify interline distances between earth covered magazines necessary to prevent sympathetic detonation. Therefore very little soil and structure debris information was recorded. Structural debris throw distances out the front of the magazines were typically very large (up to 3000 ft. for test 2 in Table 1).

Table 1. Summary of Earth-Covered Magazine Test Series Results in Reference 13

Test No.	Charge Weight (Equiv. TNT)	Charge wt / Vol (lb/ft^3)	Soil Throw (where reported)		
			Front	Side	Rear
1	2200	1.3		500 ft	
2	2200	1.3	100 ft	500 ft	300 ft
3 & 4	1290	0.78			
5	1275	1.04			
6	100,000	6.0		3300 ft	2500 ft

Since soil debris dispersion is reported for Test 2 in Table 1, and this method was developed so that it could be applied for magazines with charge weights near 2000 lbs, Test 2 was used to compare the method described in the previous section to data. Since the arch magazines used in the tests have a semicircular cross section influencing debris throw out the sides and a perpendicular cross section influencing debris throw out the back, where the roof and back wall met at right angles, the procedures for both of the typical cross sections considered by this method can be compared to the data. Table 2 shows the calculated soil debris throw distances out the sides of the arch magazine and out the back of the magazine compared to the measured values. The safety factor of 1.3 implied by this comparison is the same as that called out in Reference 2 for calculating the maximum hazardous debris distance around buildings. Therefore, the procedure for calculating soil debris throw described in the previous section, which is based in large part on a first principles approach and, in several key areas, engineering judgement, predicts debris throw with an acceptable amount of conservatism as compared to the measured values.

Table 2. Comparison of Soil Debris Dispersion Procedure with Data from Test 2 in Reference 11

Direction from Magazine	Calculated Maximum Debris Throw Distance (ft)	Reported Maximum Debris Throw Distance (ft)	Ratio of Calculated Values to Measured Values (Safety Factor)
Out sides	645	500	1.29
Out back	400	300	1.33

5.0 Application of the Method to a Missile Storage Facility

Based on the good comparison to the data shown in Table 2, this method was used to predict the maximum soil debris throw distance, and thus maximum debris throw distance, out the back and sides of several earth covered magazines at the LTV Missiles and Electronics Group test site in Grand Prairie, Texas.[10] The magazines had similar explosive weights and lower loading densities than the magazine in the test used to judge this procedure. Therefore, the very limited "validation" described above was considered applicable. The magazines in question were spaced at less than the required siting distance away from nearby inhabited building out the side and back of the magazines. For the planned explosive storage limits, the required siting distance (per Reference 1) was controlled by the default fragment protection distance of 1250 ft. As permitted in Reference 1, a fragment analysis was performed to calculate the necessary fragment protection distance more accurately. One magazine was a standard earth covered magazine with 12'x 25' plan area and a corrugated metal arch cross section covered with a minimum 2 ft of soil fill. The other magazine was a rectangular concrete box with 2 ft of soil cover over the roof. Table 3 shows the loading densities and explosive weights which were analyzed.

Table 3. Calculated Hazardous Blast Overpressure and Fragment Distances Around Magazines with Class 1.1 Explosive

Explosive Weight (lbs)	Type of Building	Loading Density (lb/ft^3)	Back: Blast (ft)	Back: Fragment (ft)	Side: Blast (ft)	Side: Fragment (ft)	Default Fragment Distance
5000	Corrugated Metal Arch Earth-covered Magazine	0.75	427	390	598	570	1250
1000	Rectangular Box Earth-covered Magazine	0.5	250	372	350	372	1250

Table 3 also shows the calculated hazardous distances out the side and back of the two magazines. Both the hazardous blast and soil debris distances were calculated because the greater of these two distances controls the required siting distance from a Class/Division 1.1 explosive storage area. It was assumed that no hazardous structural debris would be thrown further out the side and back of the magazines than the soil debris based on the data from the test series mentioned above. The hazardous blast overpressure distances were calculated with the formulas in the footnotes of Table 9-1 in Reference 1. The planned explosive material in the magazines was contained in missiles which were constructed largely of plastic, but also had a few components made of metal. The dispersion of the metal components, based on initial velocities supplied by LTV and the residual velocities calculated after the missile fragments had penetrated the surrounding soil and structure, were also considered in this analysis. The number of components was sufficiently small so that no hazardous densities (more than 1 fragment per 600 square feet) were calculated.

In summary, Table 3 shows that a significantly reduced hazardous distance was calculated out the side and back of these two magazines because the fragment analysis allowed in Reference 1, which included calculation of the maximum soil debris throw distance, was used instead of the default hazardous fragment distances.

6.0 Recommendations and Conclusions

A method for predicting the maximum distance soil debris throw from earth covered magazines has been presented and compared to limited data. The predicted maximum soil debris throw distances were 1.3 times that reported values which implies that the method predicts soil debris throw with an adequate amount of conservatism. It is recommended that this method (or any similar method) should be compared against data measured at a comparable loading density in

a comparable structure if possible before being used to predict soil debris throw from an earth covered magazine because it is thought the phenomena which affect debris throw are structure dependent and loading density dependent. Finally, the many assumptions that are necessary, and the lack of data to verify these assumptions in anything but a limited overall sense, point out a need for research in this area.

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Hazards Produced by Explosions Inside Earth-Covered Igloos

by

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ABSTRACT

The airblast and fragmentation produced by explosions inside earth-covered explosive storage structures (igloos or bunkers) have been reexamined and reanalyzed. The data were examined with the following questions in mind: (1) How do they compare with current Department of Defense Explosive Safety Standards? (2) Can the data be scaled to produce general, empirically-derived, prediction equations? Both goals were met. The data from very small-scale model tests to very large scale events collapse to a single set of prediction lines. These prediction equations are presented. It was discovered that there is a major deficiency in the data relating to the debris/fragmentation produced by explosions inside such structures.

INTRODUCTION

At the request of the Department of Defense Explosives Safety Board (DDESB), the Naval Surface Warfare Center (NAVSWC) has conducted a review of the available airblast and fragmentation/debris information that was been produced by explosions within earth-covered, explosives-storage magazines. The goals of this effort are to recommend possible changes to the applicable standards (if needed) and to provide the best available prediction tools for both fragmentation/debris and airblast. The effort began during the 1990 fiscal year with the collection and collation of the data. During fiscal year 1991, the data were compared with existing Department of Defense (DOD) explosives safety standards and the results published as reference 1. It should be pointed out that all the information developed to date has been based on full-scale testing. During the current fiscal year (1992), the results of several model studies have been included in this data base. The model studies were conducted in the United States, the United Kingdom, and France. This paper, then, updates Reference 1.

According to DOD-6065.9-STD[2], standard earth-covered magazines are approved for all quantities of explosives up to 500,000 pounds (227,273 kg) net explosive weight (NEW). The standard defines five basic types of standard magazines: (1) reinforced concrete, arch-type magazines, (2) Navy-type magazines, (3) box-type A magazines, (4) earth-covered, corrugated steel, arch-type, and (5) earth-covered, circular composite arch. During the past 40 plus years of testing, most or all of these types have been tested at one time or another. For the remainder of this report, the author will use the generic term "earth-covered igloo" when referring to all of these above-ground, earth-covered storage magazines.

The United States Air Force has conducted many tests in structures which they have termed Modular or Hayman Igloos. These are also earth-covered but of a much simpler design. These Air Force structures have not been established as a standard type of magazine, therefore, they are only approved for storage up to 250,000 pounds.

The earliest documented testing of earth-covered igloos occurred shortly after World War II. These tests were conducted at the Naval Proving Ground, Arco, Idaho. During the 1960s, tests were conducted at the Naval Ordnance Test Station (NOTS) (now, Naval Air Weapons Center, China Lake, CA). These tests examined earth-covered, steel arch type magazine construction. Beginning in 1971, the DDESB began a series of tests call ESKIMO (ESKIMO is an acronym for Explosive Safety Knowledge IMprovement Operation). The Air Force testing of their Hayman and Modular Igloos was conducted during the period 1986 to 1988. These events are discussed in more detail in Reference 1.

While this full-scale testing was on-going, a series of model tests was also being conducted. Two small-scale test series (1/50-scale and 1/30-scale) were conducted by Kingery, et. al., in 1976[3] and 1982[4]. The United Kingdom conducted two series of 1/10-scale model tests in 1971[5] and 1976[5]. The French have recently (1991) completed a series of 1/3-scale model tests[6]. These events were not considered in the compilations presented in Reference 1.

These, then, form the basis from which a data base of airblast and fragmentation has been prepared. Many of events considered for this program and presented in Reference 1 were not suitable for inclusion in the data base. The reasons for the omissions are discussed in detail in Reference 1.

Table 1 gives some details for each of the events in the data base. The information includes charge weight and type and the charge-to-volume ratio. Further details can be obtained from Reference 1, 3, 4, 5, and 6. Many tests were not conducted under standard conditions. Because of this, all the data have been scaled to sea level conditions before inclusion in the data base. Other analyses have shown that the charge-to-volume ratio is not a controlling variable for ratios greater than 0.7. For this reason each of the events shown that had tests at multiple charge-to volume ratios have been plotted as the same event.

FRAGMENTATION/DEBRIS

The DDESB defines a hazardous fragment density as "...a density of hazardous fragments exceeding one per 600 sq. ft. (56.7 m^2)." A hazardous fragment is defined as "one having an impact energy of 58 ft-lb (79 Joules) or greater." Recent interpretations by the Secretariat of the DDESB have taken the 600 ft^2 to be measured trajectory-normal as opposed to ground surface pickup. Procedures for the standardization of the analyses of debris have also been produced[7]. These standardized procedures have been used to reexamine the available debris data.

Only three events collected debris information that might be considered useful-ESKIMO I, ESKIMO VI, and HASTINGS IGLOO. Of these three, the ESKIMO I event

collected detailed fragmentation/debris data over a full 360° azimuth. ESKIMO VI presented only descriptive information, so no quantitative determinations can be drawn from it.

ESKIMO I

These data were presented in graphs in terms of debris densities as a function of range for various debris weights ($\geq$0.125 pound, $\geq$0.28 pound, and $\geq$1.0 pound). The data were converted to pseudo-trajectory normal densities as described in Reference 7 and analyzed according to the recommended procedures. Figures 1 through 3 present the results. Remember that the hazardous fragment range is the range at which the pseudo-trajectory normal density reaches a value of 1. Thus, out the front of the igloo on this test the hazardous fragment range was 3857 feet; off the side it was 2743 feet; off the rear it was 2376 feet. These correspond to scaled ranges of 66.0, 46.9, and 40.6 ft/lb$^{1/3}$, respectively.

HASTINGS IGLOO

Significant debris data were collected on four of the HASTINGS IGLOO tests--the 60-, 80-, 100-, and 150-pound tests. Fragment density distributions at distances less than 175 feet (53 meters) were not used due to the masking effect of a blast shield in front of the structure.

It is necessary to describe the test structures before the results are presented. The site was part of an abandoned Navy Ammunition Depot that was constructed during World War II. All the structures exhibited structural failures in the form of hairline cracks in the sidewalls, arch crest, backwall, and headwall. Erosion of the earth cover was observed in many cases due to a lack of maintenance. The magazine headwalls faced an earth-backed concrete blast shield. The distance between the vertical headwalls and the blast shields varied between 12 feet at the base and 15 feet at the top.

The debris results are summarized in Figures 4 through 7. On each test, debris was collected in three separate zones: 0° to 5°, 5° to 10°, and 10° to 45°. The hazardous fragment range (i.e., the range at which the hazardous fragment density becomes 1) extended to significant scaled distances out the front. The unscaled ranges are shown on each graph. These ranges correspond to scaled distances of 104.7, 122.3, 91.3, and 126.3 ft/lb$^{1/3}$. These scaled ranges are much greater that those measured on ESKIMO I. They may be affected by the poor condition of the structures existing at the time of the test. More importantly, however, the loading densities (charge weights/internal volume of structure) used on these tests were quite low; thus, the roof and sides of the structure did not fail, causing the debris to channel out the front like a shotgun. Even though the scaled debris ranges were quite large, the actual range is less than 700 feet for the 150 pound event.

AIRBLAST

DOD 6055.9-STD and NATO guidelines define several acceptable exposures which might be applied to aboveground magazines. These are:

1 Permissible exposure to airblast overpressure-barricading required: $9W^{1/3}$ (11.7 psi)
2. Unbarricaded aboveground magazine distance: $11W^{1/3}$ (8.0 psi)
3 Unbarricaded intraline distance: $18W^{1/3}$ (3.5 psi)
4. NATO Workshop distance: $20.2W^{1/3}$ (2.95 psi)
5. Public Traffic Route Distance-W < 100,000 pounds: $24W^{1/3}$ (2.3 psi)
6 Public Traffic Route Distance-W>250,000 pounds: $30W^{1/3}$ (1.7 psi)
7. NATO Public Traffic Route: $37.5W^{1/3}$(1.28 psi)
8. Inhabited Building Distance-W < 100,000 pounds: $40W^{1/3}$(1.2 psi)
9. Inhabited Building Distance-W>250,000 pounds: $50W^{1/3}$ (0.9 psi)
10. NATO Inhabited Building Distance: $58.7W^{1/3}$(0.725 psi or 50 mbar)
11. NATO Twice Inhabited Building Distance: $115W^{1/3}$ (0.29 psi or 20 mbar)

These guidelines will form the basis of comparison against which the composite data generated in this study will be compared.

Airblast information has been collected on all of the events listed in Table 1. These data have been Hopkinson-scaled to sea-level conditions and a charge weight of 1 pound. The TNT equivalence of the various types of explosives used on these tests has not been taken into account; rather, the net explosive weight (NEW) of the event has been used. Figures 8, 9, and 10 present the peak pressure out the front, side, and rear of the structure. Figures 11, 12, and 13 present the positive impulse for these same three directions. Also shown on each Figure is a least-squares curve fit to the data.

Because of the least squares fitting process, approximately 50% of the data will be above the fitted curve and 50% will be below. When the scatter in the data is small or when general estimates are required, the fact that 50% of the data can be above the fitted curve is not worrisome. However, when making estimates for safety purposes, the fact that 50% of the data could be above the fitted curve is extremely worrisome. This can be addressed in one of several ways--each of which would produce a more safety-conservative estimate. A traditional method has been to increase the NEW by a safety factor--usually taken to be 20%. A second method has been to increase the predicted pressures by a safety factor--again taken to be 20%. A third method which has been discussed is to take the upper bound of the 90% confidence interval for the predicted pressure.

Each method has its advantages and disadvantages. The third is the most rigorous from a statistical standpoint; however, making these types of estimates for non-linear curve fits is a time consuming and difficult process. The second is probably the easiest to understand, and the first is rooted in tradition. Unfortunately, the idea of increasing predicted ranges for safety predictions often meets considerable resistance. This problem is still to be resolved. The first two methods are compared in Table 2. As can be seen, the second method (that of increasing the predicted values by a factor of 1.2) is extremely conservative. The first method, that of increasing the charge weight by a factor of 1.2, is a reasonable compromise.

The equations given in Figures 8, 9, and 10 have been used to make predictions for the acceptable exposures given above. These results are presented in Table 3. Also given

in this Table are the currently accepted (Standard) values. It is evident that off the rear of the structure, the Standard is overly conservative for all exposure levels considered. Off the front and side, the Standard is overly conservative only at the lower exposure levels.

Another effort of this study was the determination of an equivalent weight (relative to the Standard) for each direction. It must be remembered, however, that this equivalence does not take into account any effects produced by the case effects of the munitions or the TNT equivalence of their fills. Figures 14, 15, and 16 present the equivalence for each direction. The average equivalence for the front and side are quite close; that out the rear is significantly lower. Out the front and the side there is a significant dependence of the equivalence on the pressure level--indicating that the pressure-distance curves in these directions are not behaving in the same manner as the standard; i.e., the curves are not parallel with the standard. Out the rear, this is not the case. The equivalence is almost independent of the pressure level--indicating that over this pressure range (0.5-10 psi) the curve is parallel to the standard.

SUMMARY/DISCUSSION

A data base of debris and airblast produced by explosions inside earth-covered, aboveground storage structures has been generated. Based on this data base, prediction equations for the airblast have been generated. These equations were then used to predict values which were compared with the current standard.

Only a limited amount of debris information exists. Before significant refinements in the standards for debris can be developed, additional information must be obtained.

Using the prediction equations developed, the equivalence (relative to the Standard) has been developed. Out the rear, the Standard grossly over-predicts the pressure (the equivalence is only about 0.3). Out the front and side, the equivalence averages approximately 0.7. At the lower pressure ranges, the Standard still over-predicts the pressure--indicating that the Standard should be changed.

Scientists in the United Kingdom have taken a slightly different approach to this problem. Instead of developing prediction equations based on the composite data, as was done here, they have developed curve fits for each separate test (ESKIMO I, NOTS 6, etc). The predictions based on the answers from all of these curve fits are then averaged to produce a single result[5]. A comparison of the two methods has indicated that the results do not differ by more than about 5%.

The Standard is currently tied to airblast data. Before the hazard ranges are changed for earth-covered igloos, the debris hazard range must also be considered. ESKIMO I has produced the only useable debris data. This data indicates that the debris hazard range exceeds the airblast hazard range, implying that any changes to the Standard must include both effects.

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6. Besson, J., private communication, January 1992.

7. Swisdak, M. M., "Procedures For the Analysis of the Debris Produced By Explosion Events," Minutes of the Twenty-Fourth Explosives Safety Seminar, August 1990.

FIGURE 1. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE--FRONT

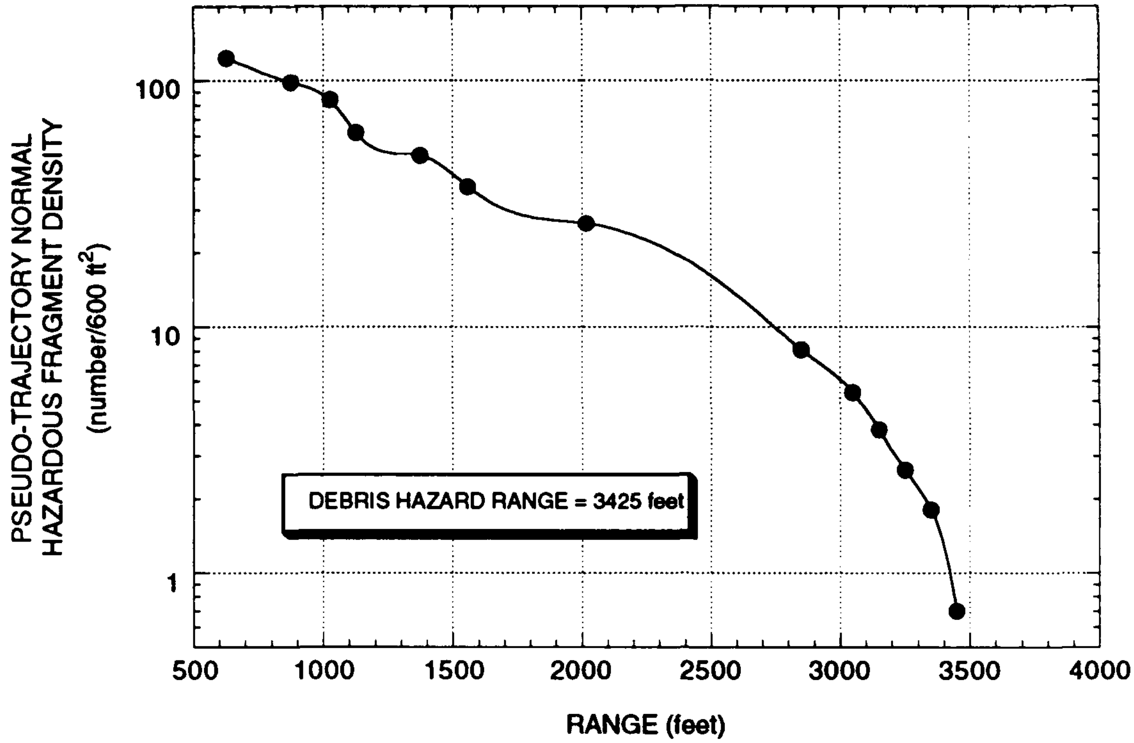

FIGURE 2. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE--SIDE

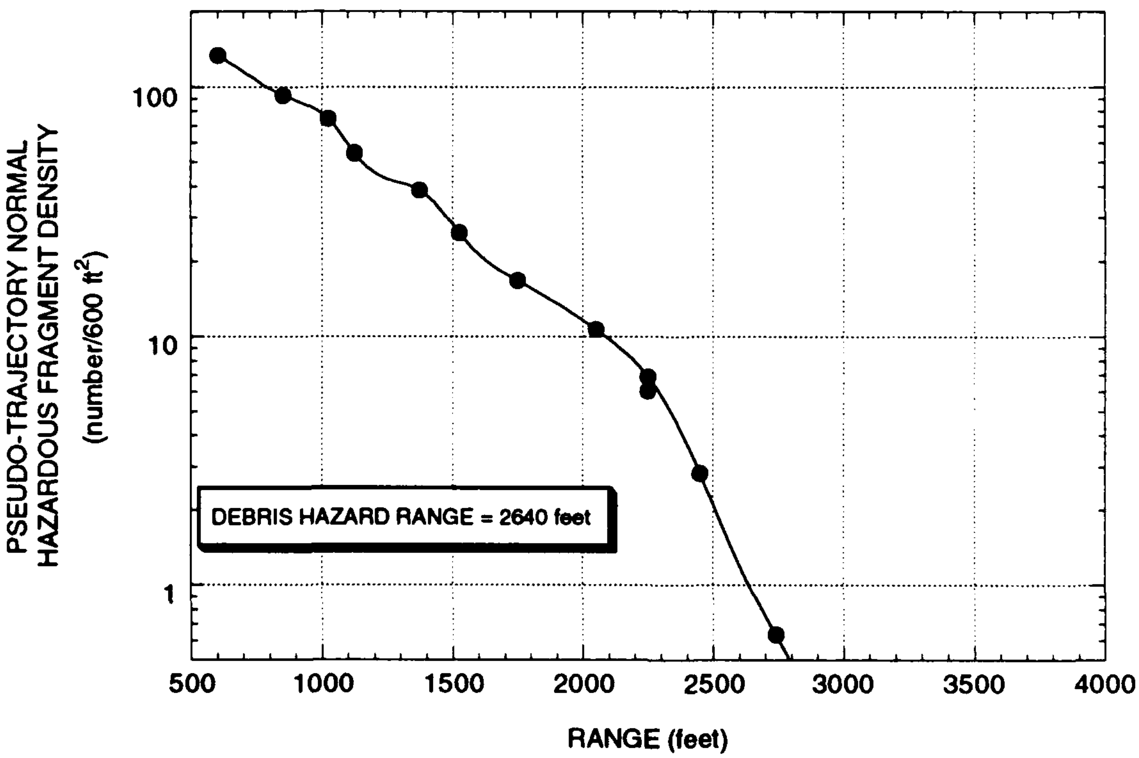

FIGURE 3. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE--REAR

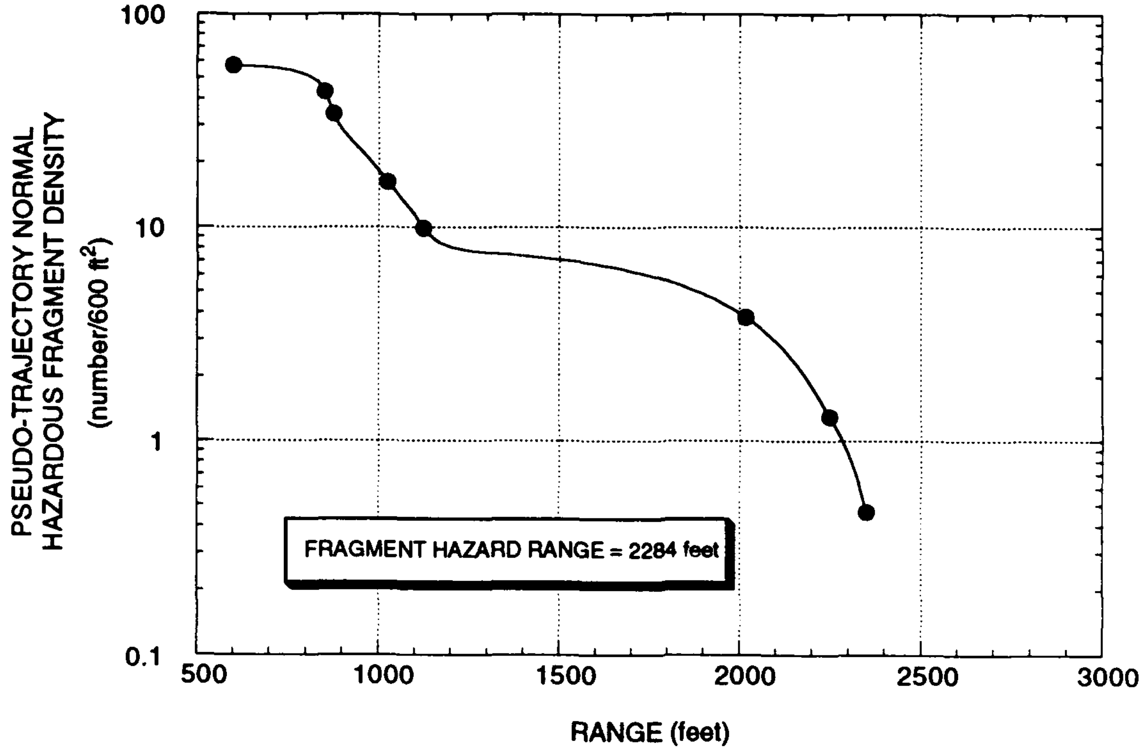

FIGURE 4. HASTINGS IGLOO (60 POUND):HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

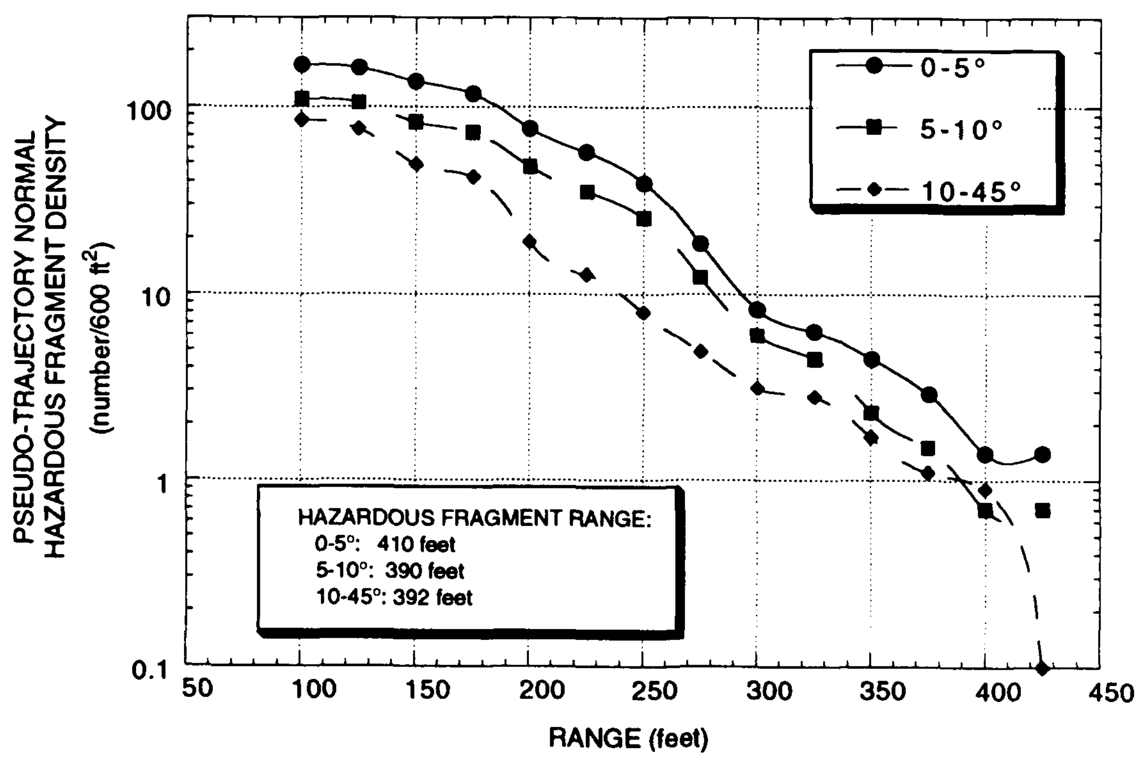

FIGURE 5. HASTINGS IGLOO (80 POUND): HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

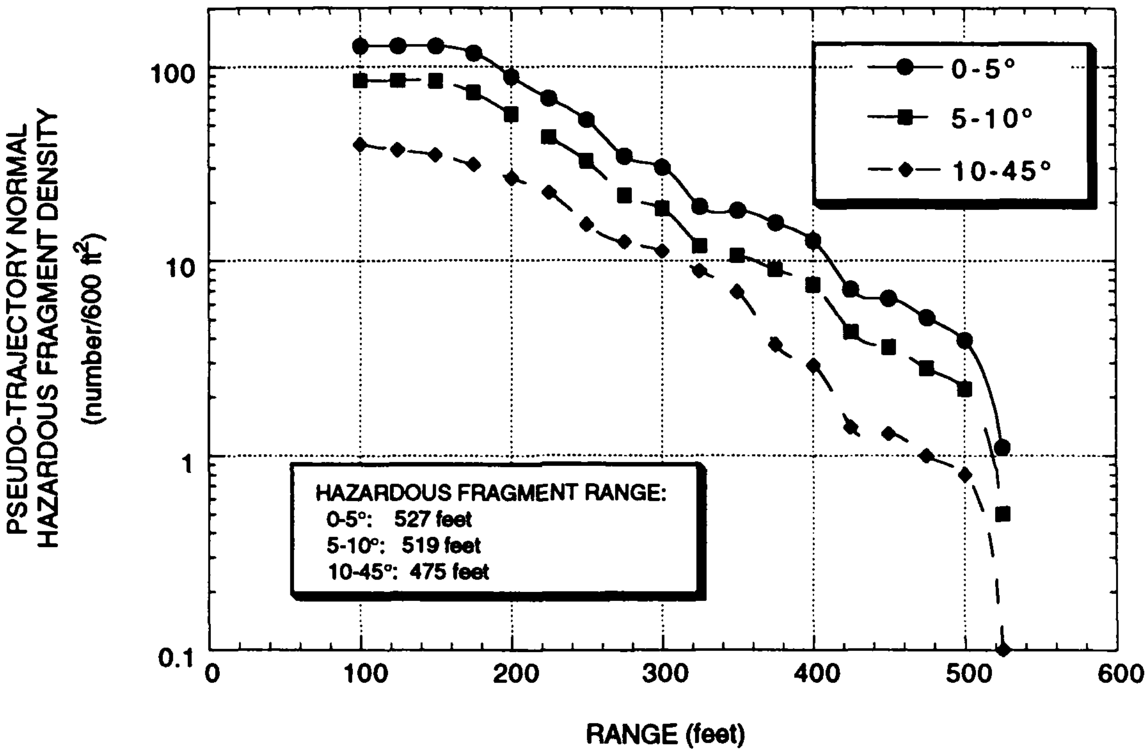

FIGURE 6. HASTINGS IGLOO (100 POUND): HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

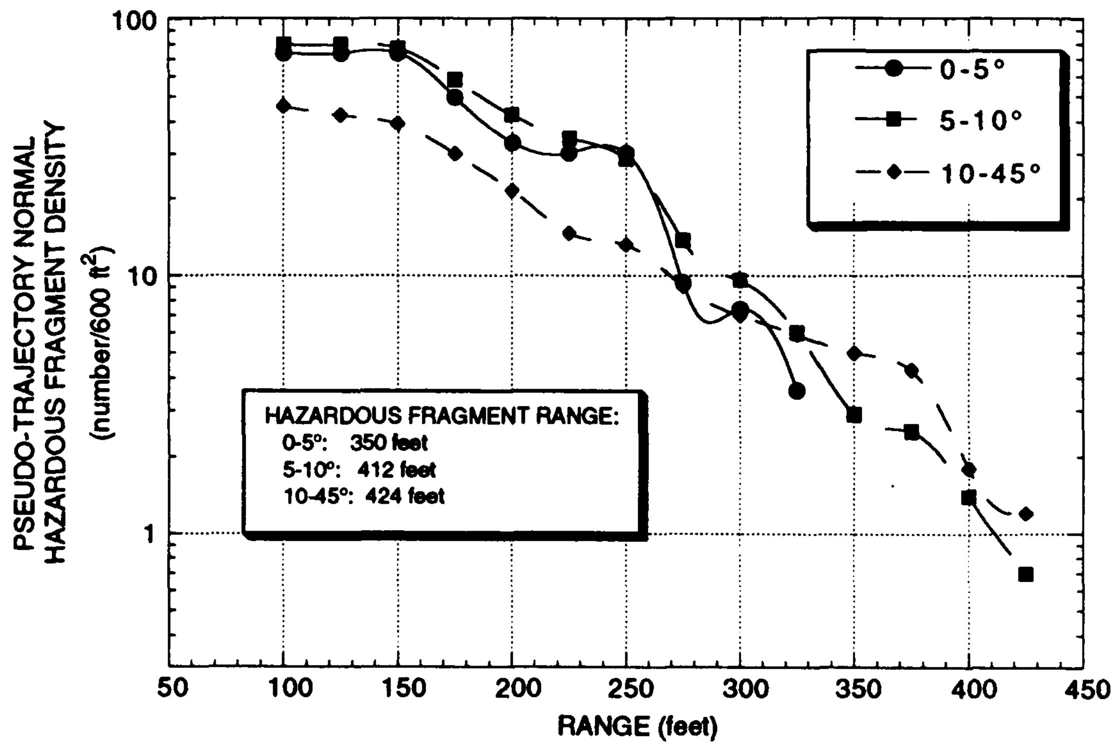

FIGURE 7. HASTINGS IGLOO (150 POUNDS): HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

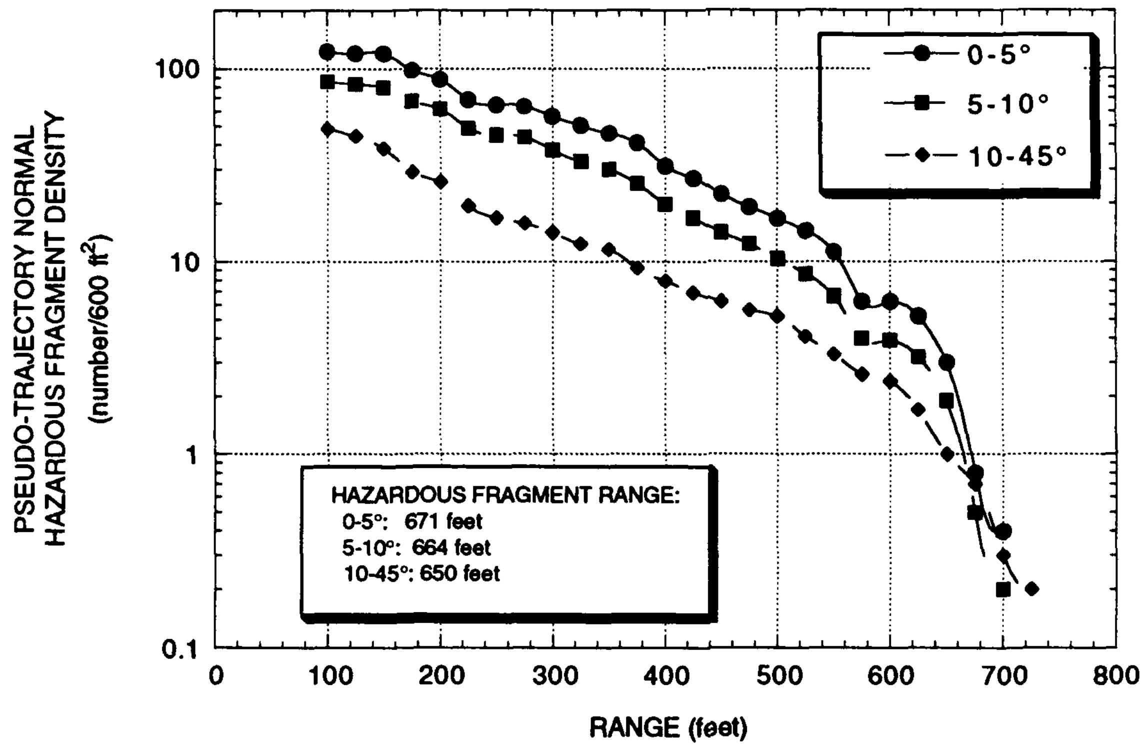

FIGURE 8. PEAK PRESSURE--FRONT

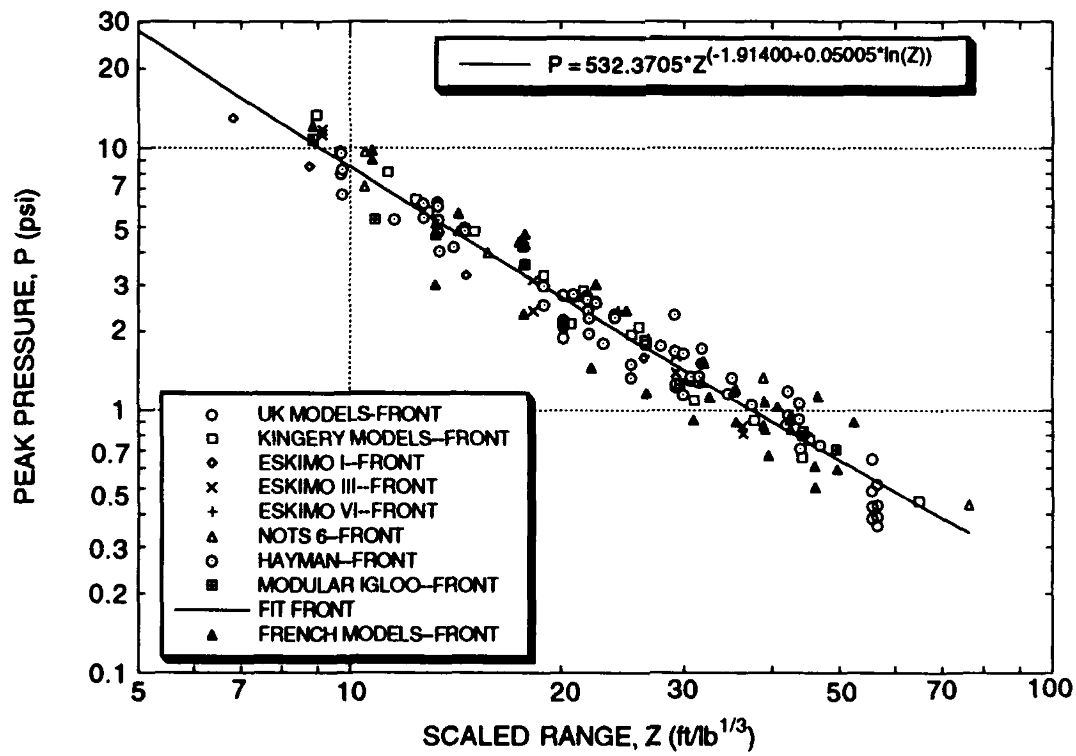

FIGURE 9. PEAK PRESSURE--SIDE

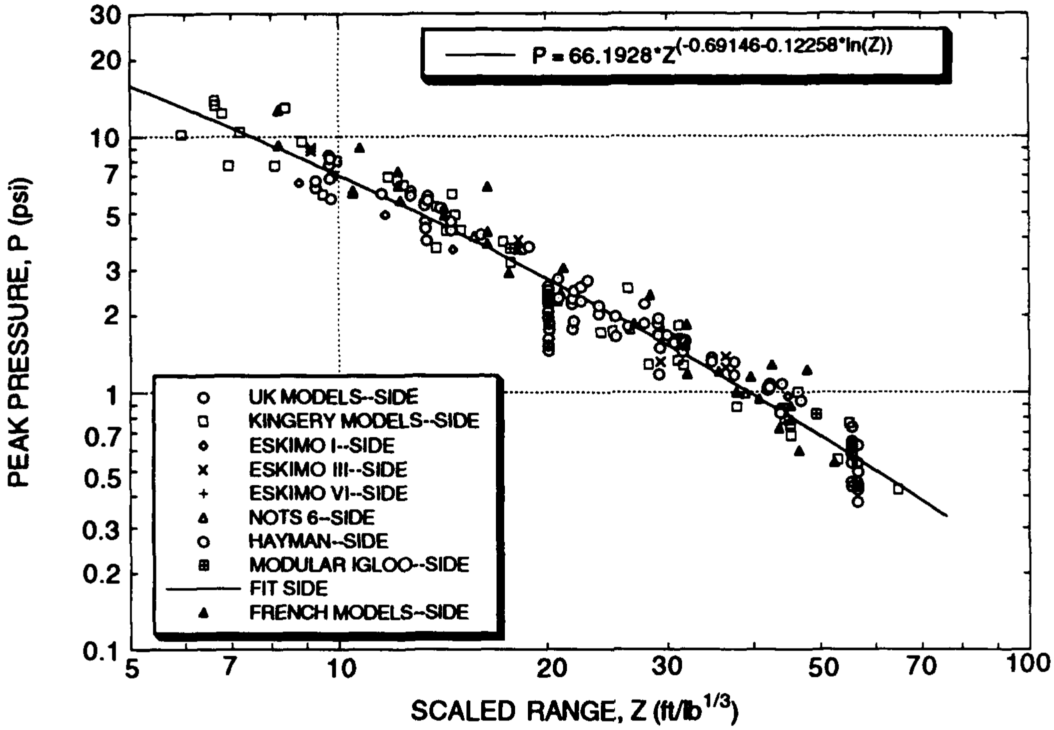

FIGURE 10. PEAK PRESSURE--REAR

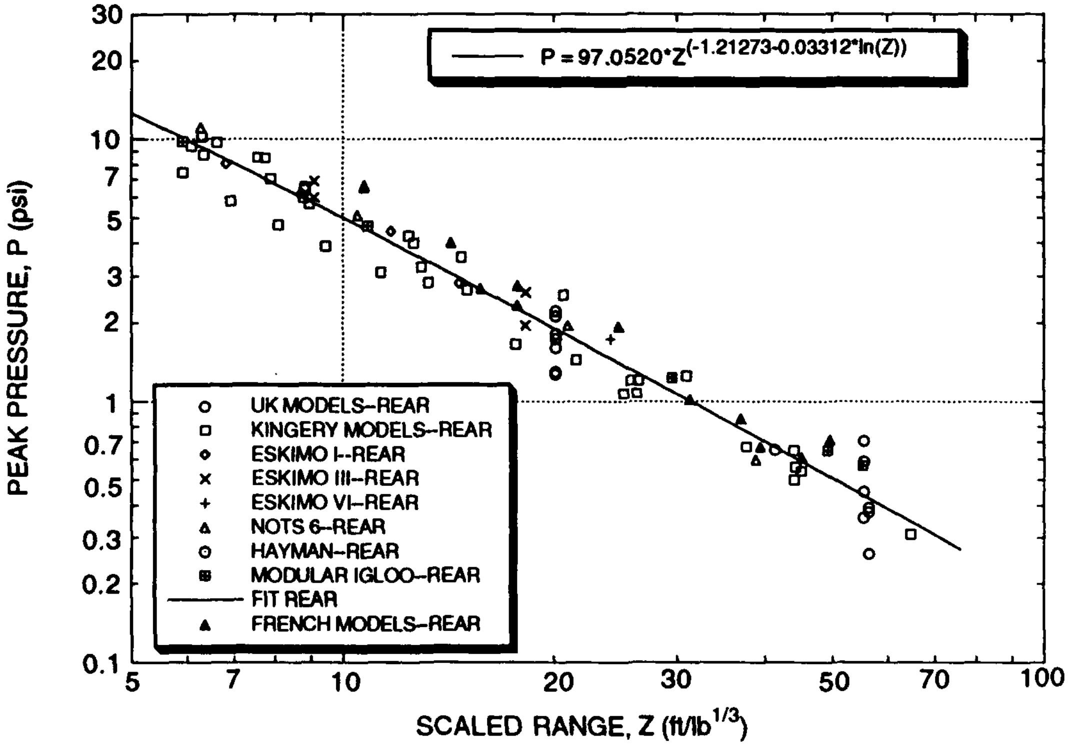

FIGURE 11. SCALED POSITIVE IMPULSE--FRONT

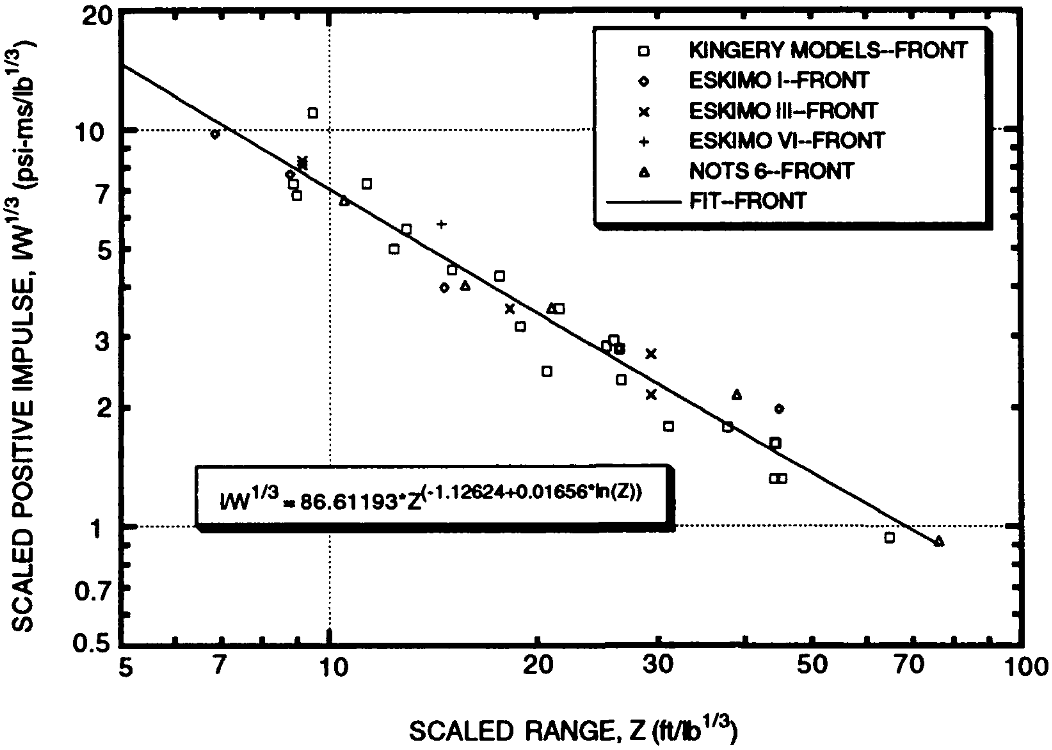

FIGURE 12. SCALED POSITIVE IMPULSE--SIDE

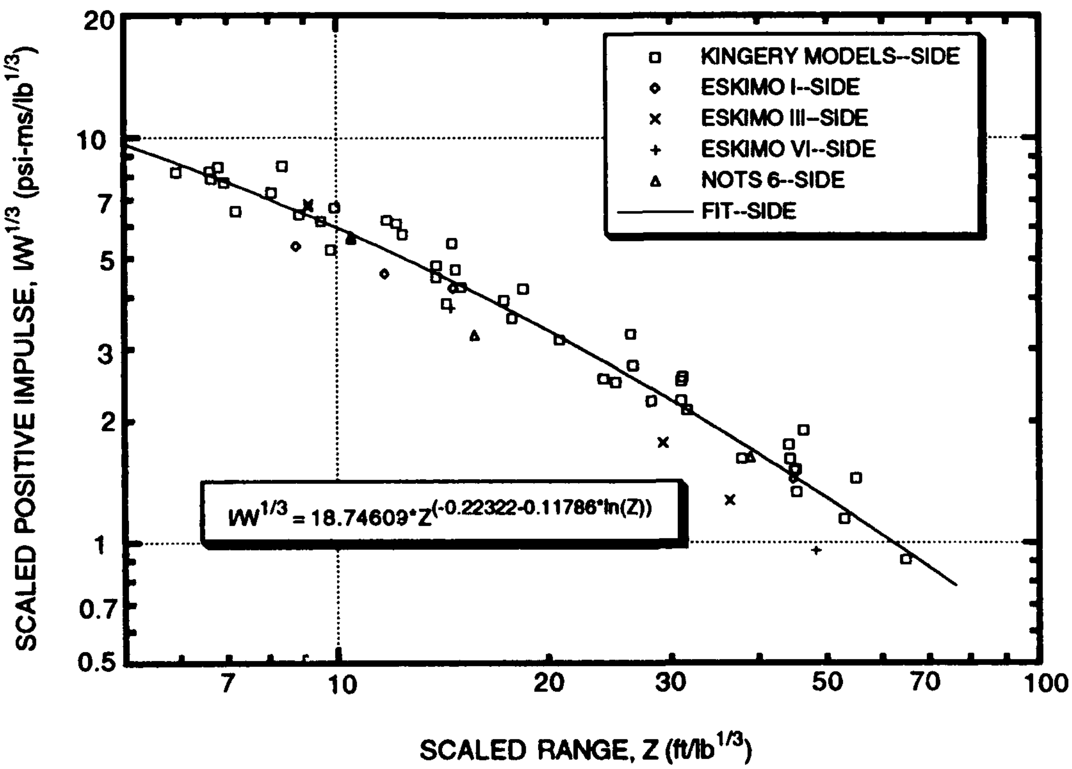

FIGURE 13. SCALED POSITIVE IMPULSE--REAR

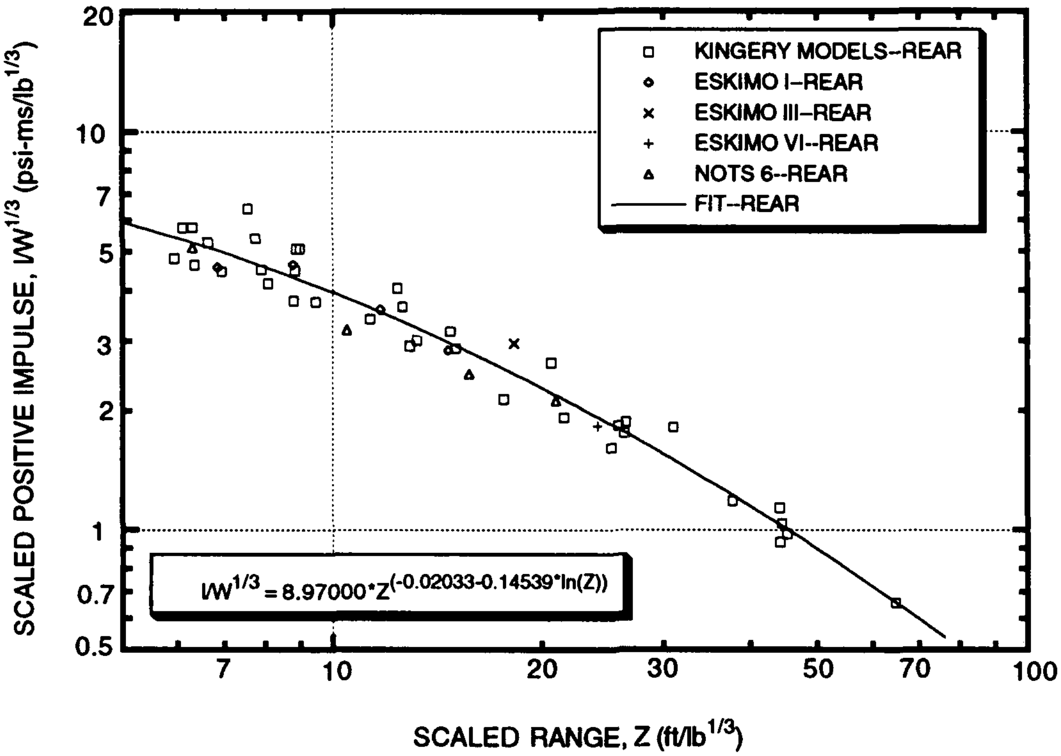

FIGURE 14. IGLOO EQUIVALENCE--FRONT

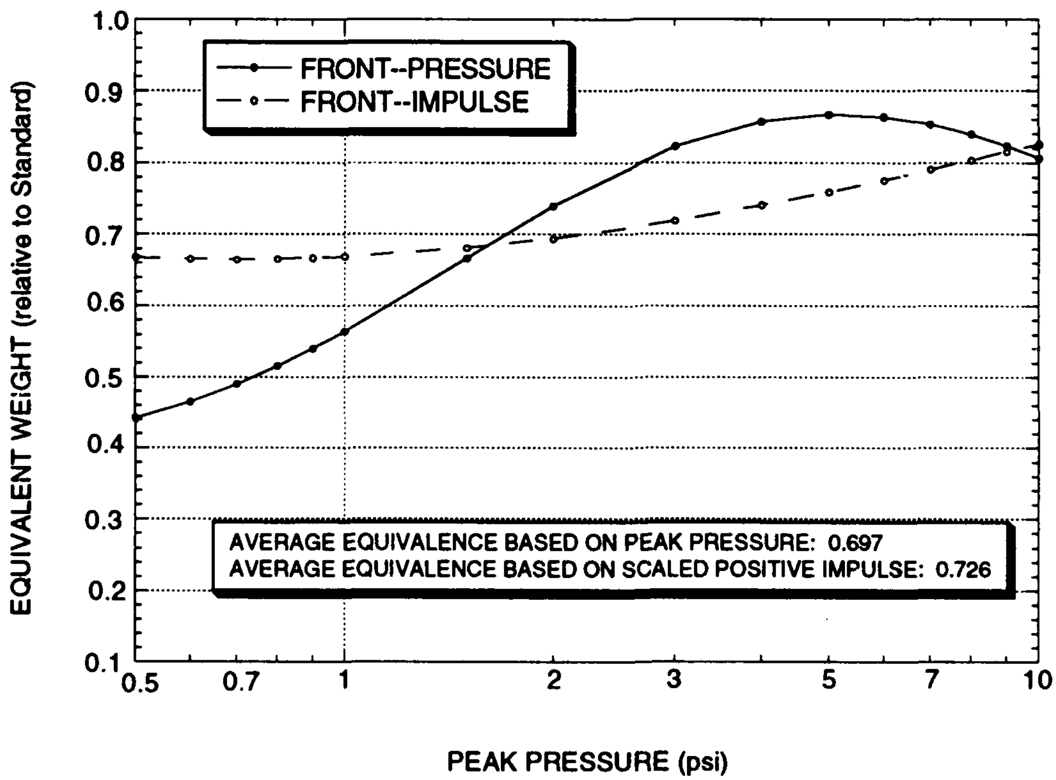

FIGURE 15. IGLOO EQUIVALENCE--SIDE

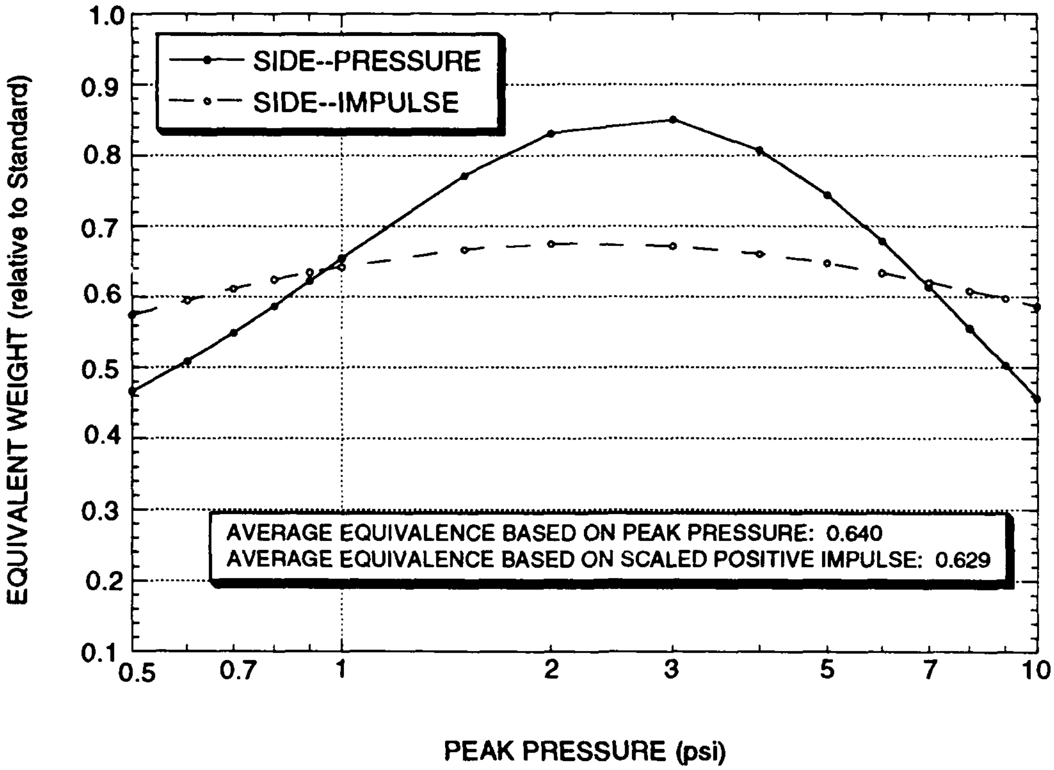

FIGURE 16. IGLOO IMPULSE--REAR

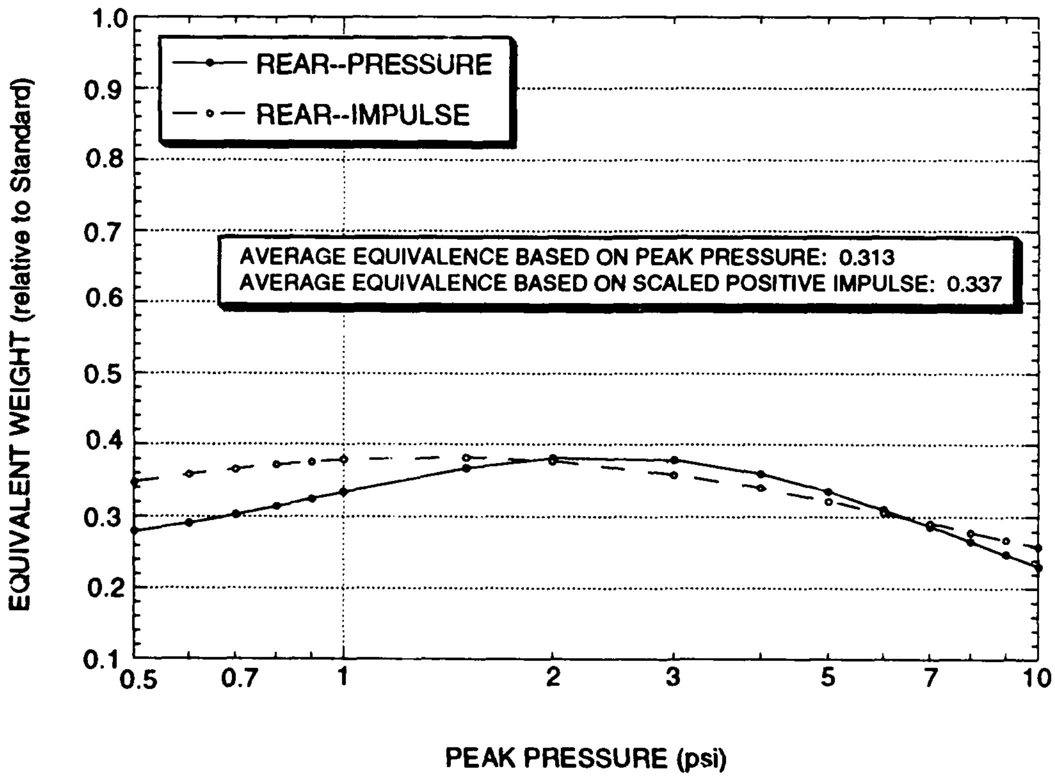

TABLE 1. PHYSICAL CHARACTERISTICS OF EVENTS IN DATA BASE

EVENT	NET EXPLOSIVE WEIGHT (pounds)	EXPLOSIVE	LOADING DENSITY (pounds/cubic foot)	SCALE
ESKIMO I	200,000	TNT	13.8	1::1
ESKIMO III	350,000	TRITONAL	17.8	1::1
ESKIMO VI	45,000	HBX-3	4.93	1::1
NOTS 6	100,035	COMPOSITION B	6.87	1::2
HAYMAN IGLOO	51,840	TRITONAL	3.24	1::1
HAYMAN IGLOO	59,904	TRITONAL	3.74	1::1
HAYMAN IGLOO	59,904	TRITONAL	3.74	1::1
HAYMAN IGLOO	120,960	TRITONAL	7.56	1::1
HAYMAN IGLOO	90,720	TRITONAL	5.67	1::1
HAYMAN IGLOO	45,360	TRITONAL	2.84	1::1
HAYMAN IGLOO	60,480	TRITONAL	3.78	1::1
HAYMAN IGLOO	60,480	TRITONAL	3.78	1::1
MODULAR IGLOO	450,450	COMPOSITION B	21.1	1::1
KINGERY (1/50)	1.81	PENTOLITE	28.6	1::50
KINGERY (1/50)	1.09	PENTOLITE	17.1	1::50
KINGERY (1/50)	0.36	PENTOLITE	5.71	1::50
KINGERY (1/30)	0.50	PENTOLITE	0.77	1::30
KINGERY (1/30)	0.80	PENTOLITE	1.23	1::30
KINGERY (1/30)	2.40	PENTOLITE	3.70	1::30
KINGERY (1/30)	4	PENTOLITE	6.17	1::30
KINGERY (1/30)	11	PENTOLITE	17.0	1::30
ESTC-1	141	TNT	7.37	1::10
ESTC-2	141	TNT	7.37	1::10
ESTC-2	276	TNT	11.4	1::10
ESTC-2	476	TNT	19.7	1::10
FRENCH	6,393	TNT	4.64	1::3
FRENCH	4,850	TNT	3.52	1::3
HASTINGS IGLOO	60	TNT	0.0035	1::1
HASTINGS IGLOO	80	TNT	0.0047	1::1
HASTINGS IGLOO	100	TNT	0.0059	1::1
HASTINGS IGLOO	150	TNT	0.0087	1::1

TABLE 2. SAFETY FACTOR COMPARISONS

NUMBER OF DATA POINTS--PEAK PRESSURE

FRONT	SIDE	REAR
159	190	83

NUMBER AND PERCENTAGE OF DATA POINTS ABOVE FITTED CURVE

	FRONT	SIDE	REAR
STANDARD LEAST SQUARES	91 57.2%	101 53.2%	40 48.2%
1.2* PREDICTED BY LEAST SQUARES	19 11.9%	26 13.7%	11 13.3%
1.2* CHARGE WEIGHT	53 33.3%	70 36.8%	27 32.5%

NUMBER OF DATA POINTS--SCALED POSITIVE IMPULSE

FRONT	SIDE	REAR
38	58	58

NUMBER AND PERCENTAGE OF DATA POINTS ABOVE FITTED CURVE

	FRONT	SIDE	REAR
STANDARD LEAST SQUARES	19 50.0%	26 44.8%	32 55.2%
1.2* PREDICTED BY LEAST SQUARES	4 10.5%	5 8.6%	14 24.1%
1.2* CHARGE WEIGHT	13 34.2%	19 32.8%	28 48.3%

TABLE 3. COMPARISON OF PREDICTED VALUES WITH CURRENT STANDARD

	PRESSURE										
	11.7	8	3.5	2.95	2.3	1.7	1.28	1.2	0.9	0.725	0.29
STANDARD (Kingery)	9.00	11.00	18.00	20.20	24.00	30.00	37.50	40.00	50.00	58.70	115.00
LEAST SQUARES-FRONT	8.26	10.34	17.04	18.93	22.09	26.70	**31.96**	**33.31**	**40.09**	**46.14**	**85.00**
1.2*NET EXPLOSIVE WEIGHT-FRONT	8.78	10.99	18.11	20.11	23.47	28.37	**33.97**	**35.40**	**42.60**	**49.03**	**90.32**
1.2* LEAST SQUARES-FRONT	9.20	11.53	19.06	21.19	24.76	29.97	**35.92**	**37.45**	**45.13**	**52.00**	**96.27**
LEAST SQUARES-SIDE	6.55	9.02	16.96	19.16	22.79	27.94	**33.63**	**35.05**	**42.03**	**48.01**	**82.14**
1.2*NET EXPLOSIVE WEIGHT-SIDE	6.96	9.58	18.02	20.36	24.22	29.69	**35.74**	**37.25**	**44.66**	**51.02**	**87.29**
1.2* LEAST SQUARES-SIDE	7.66	10.43	19.32	21.77	25.79	31.50	37.78	39.35	**47.03**	**53.61**	**90.97**
LEAST SQUARES-REAR	**5.30**	**7.06**	**12.94**	**14.64**	**17.50**	**21.69**	**26.47**	**27.69**	**33.82**	**39.25**	**73.01**
1.2*NET EXPLOSIVE WEIGHT-REAR	**5.64**	**7.50**	**13.76**	**15.56**	**18.60**	**23.04**	**28.13**	**29.43**	**35.94**	**41.71**	**77.59**
1.2* LEAST SQUARES-REAR	**6.09**	**8.08**	**14.76**	**16.69**	**19.92**	**24.65**	**30.06**	**31.44**	**38.35**	**44.47**	**82.44**

NOTES:

(1) All distances shown are in ft/lb^1/3

(2) Numbers in BOLD represent pressures attenuated by earth-covered structures relative to values for aboveground structures at the same indicated scaled distances

AN APPROACH TO THE SAFE MANAGEMENT OF THE STORAGE OF MILITARY EXPLOSIVES BASED ON QUANTITATIVE RISK ASSESSMENT

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INTRODUCTION

1. The procedures currently used by the United Kingdom Ministry of Defence (MODUK) to control the hazards associated with the storage of explosives are based on criteria known as Quantity-Distance, or QD, Rules. These specify minimum distances between stored explosives and specified exposed sites to give an assurance that accidental explosion will not cause unacceptable damage at the exposed site. They are primarily concerned with damage to buildings rather than risks to individuals. QD Rules are based either on historical data, for instance WWII bomb damage data, or on more recent experimental evidence.

2. The rules apply to individual storehouses or stacks of explosives and lead to a method of control based on licences. Under the terms of a licence, the quantities of the various classes of explosive substances and/or articles which may be kept in a particular place or storehouse are restricted according to the separation distances from other buildings or areas with public access.

3. In Great Britain the keeping of explosives is controlled by the 1875 Explosives Act. MODUK is exempt from the requirements of this Act. However, MODUK is not exempt from the more general

requirements of the Health and Safety at Work etc Act 1974. This Act places obligations on employers to ensure, so far as is reasonably practicable;

a) the health, safety and welfare at work of all their employees and

b) that persons not in their employment are not exposed to risks to their health and safety.

Implicit in these duties is the need to assess risks in order to demonstrate that all reasonably practicable measures to reduce them have been taken. More recent and explicit regulations about to come into force require employers to assess the risks to the health and safety of employees and others as a result of their activities. The complexity of these assessments depends on the nature of the activities being carried out at the workplace but for sites presenting a major hazard, a quantitative risk assessment (QRA) is likely to be required.

4. Statutory compliance is therefore an important driver of studies of QRA by MODUK. However, in addition to ensuring compliance QRA has other advantages. It helps managers to identify clearly the major contributors to risk at a site and provides a tool for investigating the effectiveness of measures to reduce risk. If a QRA establishes that risks at a site are intolerably high, then the method can be used to examine proposals for improvement, allowing the most cost effective remedies to be implemented. The use of QRA thus offers more flexible management of explosives safety than can be achieved

under prescriptive QD Rules, with the prospect of reducing costs and at the same time enhancing safety.

5. For all these reasons, MODUK, through the Explosives Storage and Transport Committee (ESTC) has investigated risk based approaches to the control of its explosives sites. This paper describes those investigations to date, outlining the methods which have been adopted and proposing how they might be applied to give a safe and cost-effective system for the management of the storage of military explosives.

AIM

6. To outline the development within MODUK of a QRA method applicable to the management of explosives storage and to discuss the notion of the tolerability of risk.

THE QRA METHOD

7. In outline, the approach adopted by MODUK permits estimation of the maximum annual risk of fatality for an individual at each site exposed to the hazard from handling and storing explosives. The risk in this instance is expressed as the product of the estimated maximum frequency of initiation and the probable lethality consequent on the worst credible accident.

8. To generate the frequency of initiation, details are required of the quantities and types of explosives stored. The subsequent calculation is based on either historic accident data (Level 1 Method), or on failure mode analyses and fault trees (Level 2 Method). Important factors to be considered in the case of military ammunition depots include any on-site processing, within site transport or the possibility of malicious damage

together with external hazards such as adverse weather, accidental aircraft strike or other nearby hazardous activities.

In both the Level 1 and Level 2 Methods the estimation of the frequency of initiation relies on the maintenance of consistent and controlled standards within the site. This has to be confirmed by evaluating both internal and independent audit reports.

9. Reliance on accident data suffers from major flaws. Firstly, there are few accidents on which to base any estimates; secondly building standards have changed substantially since WWII so that damage effects and hence the risks of harm to individals have also changed; thirdly new explosives and articles may present substantially different hazards than those of earlier generations and finally every accident which has occurred should lead to changes in operating procedures which reduce the risk of recurrence. However, the data do allow an estimate to be made of the maximum credible initiation frequency for all types of explosives in MODUK storehouses.

10. A study of the available data has lead to the conclusion that major incidents of fire and explosion involving explosives materials stored by or for MODUK have occurred at a rate of 1.5×10^{-5} per storehouse-year over the period 1946 to 1990. It is not possible to derive initiation frequencies for individual explosive items from the data but these figures are essential to the QRA method. They have therefore been derived from a survey of expert opinion in which a group of experts in weapon and explosive safety individually ranked a series of substances and articles in order of expected accidental initiation frequency.

These experts agreed that the greatest initiation hazard was presented by gunpowder. The historical data, which may be incomplete, indicates that there have been some 3000 gunpowder storehouse operating years in the UK since 1945 with no major storage incident. This suggests an upper bound no greater than 1 in 10^{-3} per storehouse-year for accidental initiation of this, the most sensitive explosive in UK service.

11. The experts were then asked to estimate relative frequencies of initiation for the articles and substances they had ranked and on this basis it was concluded that, for the least sensitive explosives and articles, an initiation frequency of no greater than 1 in 10^{-6} per storehouse-year was appropriate, giving a scale broadly consistent with the overall UK incident frequency. This scale may well be overly pessimistic but it is difficult to justify lower figures on the basis of the limited data available. The end product is a means of estimating initiation frequency based on history and expert knowledge which, although far from being perfect, provides a reasonable and defensible figure. Quite deliberately, at every stage of the estimation conservative assumptions are made so that frequency estimates should err on the side of caution.

12. The Level 2 Method uses failure mode analysis to generate fault trees and, given a set of base event frequencies, an estimate of initiation frequency can be made and direct comparisons between different routes to initiation are possible. Here again the main problem is the lack of hard data on which to found base event frequencies. In a complex chemical or nuclear plant the routes to hazardous events are likely to involve component failures and techniques exist to estimate the

likelihood of such failures. The factors leading to accidental initiation of explosives in storage are difficult to identify in purely mechanical terms and are more difficult to quantify. Factors such as inadequate training, ambiguous instruction, human error or even malicious behaviour may play a significant role.

13. The lethality consequence models evaluate the effects of blast, weapon fragments, building debris and thermal radiation on people, both inside normal domestic housing and in the open. Normal procedures assume an explosion on the surface, but models are also available for underground explosions. The development of these models, and their incorporation into software, has formed a major part of the work.

14. Each model is derived in essentially two stages. In the first the physical output resulting from initiation of the explosives being stored is estimated. The complex effects of the shock, heat and fragments generated by an explosion on buildings make this a difficult task. There is some experimental data, including data generated to support QD Rules but in some cases models have to be derived from basic principles with little or no direct verification. In the second stage the effect of the physical output on exposed individuals must be estimated. Again, this is a difficult task, particularly for individuals at some distance from the source of the accidental event. Historical data can be helpful here and in another report to this Seminar, Dr Hewkin of the ESTC Risk Assessment Study Team will discuss detailed work relating to one of the consequence models which involves a survey of accident records.

15. The consequence models we have developed in this work may well be of value to other workers involved in the evaluation of explosion effects quite independently of their use in QRA.

16. Application of the QRA method requires a detailed understanding of all its components, and the way in which they interact together with a good knowledge of explosives properties. Unlike QD Rules, which can be applied by site managers locally based on straightforward training, QRA requires and will continue to require expert judgement and a dedicated team for its application.

17. To carry out an assessment, members of the expert team need to visit and to survey the site of interest to determine the inputs to the QRA and the initiation frequency and consequence models to be employed. The procedure then provides a method for estimating the maximum risk expected for an individual continuously exposed (indoors or out) at any point on or off the site. The output will normally be the risk of fatality at each exposed site for a single continuously exposed person, per year, but the major contributions to each risk can also be identified.

18. Once the risk to an individual has been estimated, its tolerability can be assessed in comparison with published criteria or the risks associated with other activities.

19. In addition to giving an estimate of individual risk, the method can also provide an estimate of societal risk, the relationship between frequency and the number of people suffering from a specified level of harm (death in the case of the MODUK QRA method) in a given population from the realisation of

specified hazards. Societal risk measures the risk to the population as a whole and is important for two reasons:

a) in many cases a particular individual may be exposed to the hazard for only a short time, for example while driving past an ammunition store on a public road, in which case the risk to the individual may be tolerable but the large numbers using the road may nevertheless render the total societal risk intolerable.

b) society tends to find accidents involving large numbers of fatalities proportionately less aceptable than accidents involving one only

Societal risk is usually expressed in terms of F/N plots of the frequency F of N or more deaths occurring as a result of an accident as a function of N.

20. The tolerability of societal risks can, as with individual risk, be assessed by comparison with published criteria or with risks associated with other industries. Here, however, any criterion will take the form of a line on an F/N plot with greater negative slope indicating a greater aversion to multiple fatalities.

TOLERABILTY OF RISK

21. Several times in this paper reference has been made to the notion of the tolerability of risk. This is a difficult concept inviting questions as to why one individual's activities should be allowed to put another individual at risk. However, everyone

take risks - we drive vehicles, we cross the road, we ski or hang-glide - and everyone benefits from activities which place themselves and/or others at risk, for example a thriving chemical industry. We would very quickly complain if hazardous substances such as gasoline were no longer available to us. Implicitly at least, some degree of risk is accepted so that a benefit may be enjoyed.

22. The question to be addressed therfore concerns the level of risk that it is reasonable to impose on exposed populations so that stores of military explosives and ammunition can be maintained. There is an almost universal agreement on the need for nations to maintain adequate defences and therefore a recognition of the benefit to society of the ammunition stockpile. However, as an MOD employee and from the comfort of my office many miles from the nearest explosives store, my concept of what is tolerable may be quite different from that of someone not employed by MOD who lives next-door to one of our depots.

23. In the UK, the Health and Safety Executive (HSE) has taken a lead in addressing such issues. The HSE is the body responsible for enforcing health and safety legislation, and it provides guidance on how compliance with the very generally framed law can be assured. As a part of this process, the HSE has produced a series of well written and useful documents on QRA and risk tolerability and has generated a conceptual framework within which the tolerabilty issue can be discussed. The framework is expressed in Figure 1.

24. This framework draws heavily on the statutory requirement in the UK to demonstrate that risks are as low as is reasonably practicable - the so-called ALARP principle. It is based on individual risk but the principles apply equally to societal risk. Risks above a certain level are intolerable and require immediate action to reduce them irrespective of cost. At a substantially lower level is a region where risks are broadly tolerable. This is a region where, provided there is a benefit to be gained and proper precautions are taken the risk does not cause us to alter our normal behaviour. Between these two levels is the important ALARP region.

25. In the ALARP region risks must be reduced, as the law demands, so far as is reasonably practicable. The test of reasonable practicability is that the costs of extra safety should not be grossly disproportionate to the benefits accrued. A cost-benefit analysis is essential.

26. The HSE framework derives from UK legislation but it has a broader applicabilty in that it provides a model within which managers can use QRA to assist them in decisions about the cost effectiveness of resource commitments.

27. Determining criteria against which the tolerability of risks can be assessed is difficult. However, the HSE has given some guidance on this. The levels are set not by some absolute scientific law but by what society will tolerate at any given time. Almost certainly this degree of tolerance has reduced over the years, people expect life to become safer and expect to die naturally rather than by accident. On the other hand, in time of war greater risks would be expected and accepted and at any time

we might expect those likely to benefit the most to tolerate the greater risk. In the UK no employment involving any significant number of people is estimated to present an individual with more than a 1 in 10^{-3} chance of death in one year. This level is often quoted as defining the limit of tolerability. At the other end of the scale, figures of the order of 1 in 10^{-6} are regarded as falling at or close to the limit where the risk might be regarded as being negligible.

28. It would be quite wrong to regard these values as set in tablets of stone. Society's expectations will undoubtedly increase, they may vary from place to place and, of course, they may well be influenced by the size of the tax bill! Different activities give different benefits and, in societal risk terms, those most exposed to risk may take a different view from those who benefit at little risk to themselves. Ultimately, decisions on the tolerability of risk are political rather than technical but we might reasonably expect the reduction in world tensions over the past few years to be reflected in reduced tolerability of risks associated with defence activity. Whether that means that the public would expect a lower risk from such activity than from, say, nuclear power plant or chemical plant is another matter.

29. For all these reasons MODUK has avoided setting any tolerability criteria and does not envisage using QRA as an absolute tool, determining what may or may not be done. The view taken is that such criteria could only be derived from informed political debate and that such debate still has a long way to run. However, that does not mean that QRA does not have immediate practical application.

THE APPLICATION OF QRA

30. QD Rules have a number of important attributes. They are prescriptive and can be applied by managers locally without the need for expert support. They provide unambiguous conclusions. Over many years they have been a key feature in achieving what is a very high standard of explosives safety within MODUK. It would be foolish to cast aside these advantages. On the other hand, QD Rules do not provide any explicit assessment of risk. We therefore intend to complement QD by QRA, not to replace it.

31. We see QRA as underpinning QD, demonstrating that the risks of operating under a QD regime are tolerable. Where QRA shows that risk levels are relatively high, the major factors contributing to the risk can be identified and risk reduction measures assessed and implemented in line with the ALARP principle. Given that the assumptions on which the QRA is based do not change, then the assessment and management of the site can continue under QD Rules in the knowledge that this provides a tolerable upper limit on the risk.

32. The combination of QD and QRA thus provides an assurance that risks are capped provided that the QRA remains valid. This limits the need for the expensive QRA process to be repeated to occasions where there are significant changes in site operation to be considered. Such changes would include changes in the site layout, including both explosive and non-explosive buildings, changes in staffing levels within the site and any changes in land use and population density outside the site but within the area potentially at risk. Perhaps most significantly, changes in management procedures must also be included. A system of explosives safety management involving licensing, inspection and

audit must be an integral part of a combined QD/QRA control system.

33. There is, of course, pressure in the regulatory system and from the general public to ensure that risks decrease with time. The standards acceptable to our parents are not acceptable to us and our children will expect better still. These pressures are recognised in the ALARP principle since what is not practicable today may well be practicable tomorrow. A QD based system alone cannot help here but QRA provides an effective mechanism by which to bring about such improvements.

34. One feature of present QD Rules is that it is far from clear that explosives of different hazard divisions are treated in a way that ensures that they present equal risks. In fact this is almost certainly not the case. QRA will allow the risks associated with the different classes to be compared and for them to move over a period of time towards comparability. This should not, of course, be taken as an argument for increasing risks to the lowest common denominator, that is unlikely to impress either the regulators or the public, but it will help to curb unnecessary expenditure and to target resources where they will have most effect.

35. One final point should be made, in the UK we see the study we are conducting on storage as being a pilot. If the outcome is successful we would expect to extend the method to cover other situations involving explosives risks, including transport, range control, testing of all up rounds and demilitarisation.

CONCLUSIONS

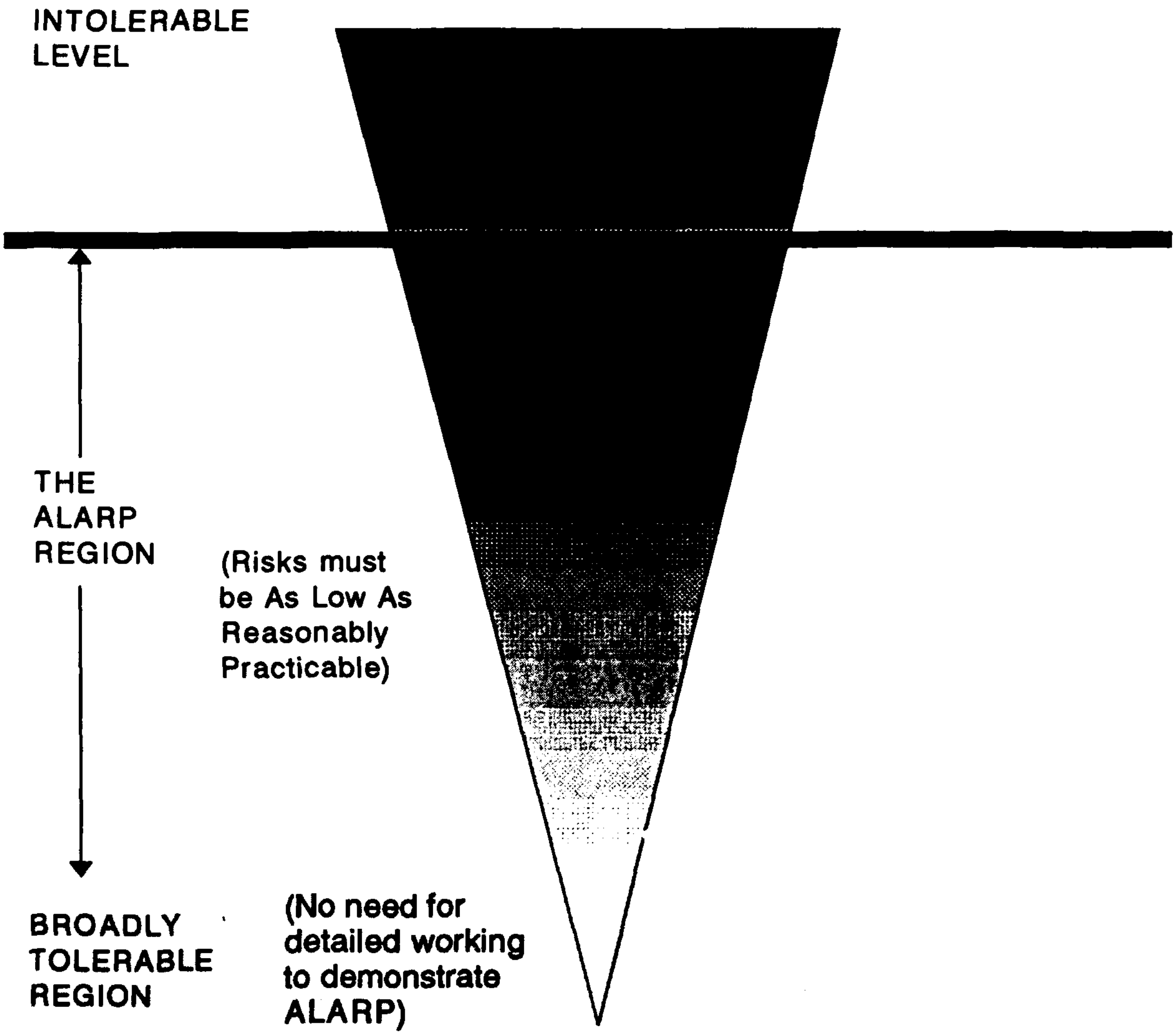
36. Within the UK Ministry of Defence we are developing methods which will allow us to determine the maximum credible risk associated with our explosive storage activities. The first generation of such methods is now close to being ready to be applied and is being assessed against our present storage regime.

37. We envisage these QRA methods being applied to complement existing QD Rules rather than to replace them. They will demonstrate where our operations present a tolerable level of risk to MOD personnel and to the public and, where risks are assessed as being relatively high, will identify the major contributors and the most effective means of risk reduction.

38. QRA will also provide a valuable management tool, allowing the effects of changes in site layouts, handling procedures and management policies on explosives safety to be assessed.

39. The techniques currently being developed for the assessment of initiation probabilities and their consequences are relatively primitive. There is scope for substantially more work to be done to improve the accuracy and precision of the models we use and we would welcome collaboration with others in this work.

Figure 1. LEVELS OF RISK AND ALARP



(Adapted from a diagram in "The tolerability of risk from nuclear power stations", HSE, 1988.)

AN INVESTIGATION INTO THE FEASIBILITY OF USING RISK ASSESSMENT METHODOLOGY FOR LICENSING EXPLOSIVES HANDLING PORTS

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INTRODUCTION

The system of control imposed on explosives movements through ports in Great Britain is based on the well established principle of quantity distances, ie restrictions are placed on the types and quantities of explosives that may be moved so as to ensure limited consequences in the event of an accident. Explosives limits for individual ports are set out in formal licenses issued by the UK Health and Safety Executive (HSE). The HSE has recently licensed GB ports under the 1987 'Dangerous Substances in Harbour Areas Regulations' (DSHAR)[1]. In a number of cases building development around ports has resulted in lower license limits than the operators would desire. Thus much interest has been expressed in the possibility of using quantified risk assessment (QRA) for justifying higher limits.

This paper considers one way in which a QRA-based system of ports licensing might be introduced in Great Britain and looks at the advantages and disadvantages of such a move.

HOW MIGHT QRA BE INTRODUCED?

The Control of Industrial Major Accident Hazards (CIMAH) Regulations [2] requires safety cases to be prepared for certain installations in the UK where large quantities of flammable and toxic substances are handled (explosives installations are currently excluded from these regulations). Regulation 7 of CIMAH requires a person in control of a 'top-tier' industrial activity to submit to the HSE a written safety report. Such a report is to provide information about the dangerous substances, the installation, the management system, potential major accidents and describe the measures taken to prevent, control or minimise the consequences of any major accident. Although not a mandatory requirement, the use of QRA in support of safety cases is now well established in the UK. It is suggested that a QRA-based system of ports licensing could operate on a similar principle: ie operators could apply to HSE for higher license limits than those currently granted and justify those higher limits by the

preparation of a safety case, of which a QRA would be a major component. In practice the application of a risk-based approach to liçensing may lead to real safety improvements through greater operator awareness of risk generating activities. The HSE would subsequently need to evaluate the safety case submitted by the applicant and, if this were then to be included as part of the draft license, account would have to be taken of public comment before the license could be issued.

A precedent for such a system was in fact set as far back as the early 1980s. At this time QRA was used to provide a basis for essentially a political decision to be made, allowing higher limits at one port where there had been a particularly difficult encroachment problem (the port was not subject to DSHAR at that time). The QRA was undertaken at the operator's expense - though the resources required by the HSE in evaluating the operator's report were considerable. This immediately highlights one disadvantage of QRA: it can be a costly technique. The high cost arises from the detailed nature of the analysis that may be required to be undertaken in an assessment. The extent of analysis that would be required in a QRA undertaken in support of an explosives license is discussed in the following section of this paper, together with details of the information that would need to be set out in the applicants report

WHAT INFORMATION SHOULD BE CONTAINED IN A QRA-BASED APPLICATION FOR AN EXPLOSIVES LICENSE?

It is would be essential for the applicant's written report to contain sufficient information to enable structured evaluation to be undertaken by the HSE. The information requirements can be grouped under four headings:-

1 Information relating to the dangerous materials

2 Information relating to the site

3 Information relating to management systems

4 Information relating to the potential major accidents

The information provided under headings 1, 2 and 3 would allow a complete description to be built up of the procedures by which the operator would move explosives through the port, as well as enable those factors to be identified which would bear on the risk of the operation; such information would provide essential background detail to the QRA. The information provided under heading 4 should be sufficiently detailed to allow the HSE to undertake structured evaluation of the method employed by the operator to estimate levels of risk.

1 Information relating to the dangerous materials

The applicant should specify:-

a. For each vehicle carrying explosives into or out of the port, the names of the explosives substances/articles carried, together with methods of packing, Hazard Classification Codes and the net explosives quantity (NEQ) of each type of substance/article in the load.

b. For each explosives ship berthing at the port, the same information as that outlined in a.

c. The number of ships per year on which explosives are to be loaded - and from which explosives are to be off-loaded.

The above information would be required to help establish both the likelihood of occurrence of an explosives accident (which would in part be a function of the types and quantities of explosives handled) and the consequences of an explosives accident (which would in part be a function of NEQ).

d. The names and quantities of any other dangerous substances which may be present at the port at the same time as explosives. The hazards which these other substances pose should be mentioned.

This last point is important as a full assessment of the risks from the handling explosives in ports must take account of possible "domino effects" arising from potential interaction between explosives and other types of dangerous commodities.

2 Information relating to the site

a. A map of the port and its surrounding area to a scale large enough to show any features that may be significant in the assessment of the hazard or risk associated with the movement of explosives through the port. The map should show the location of the port and its relationship to local features such as:-

   (i) residential areas;

   (ii) premises where evacuation would prove difficult, eg schools, hospitals, prisons, old peoples homes and sheltered accommodation etc;

   (iii) industrial and commercial premises;

   (iv) other hazardous installations;

   (v) transport features, eg major roads and railways;

   (vi) recreational areas;

(vii) vulnerable features of the environment, eg buildings of vulnerable construction.

In the case of GB ports, an Ordnance Survey map of scale 1 to 10 000 should provide the necessary detail. The most up-to-date map available should be used and any recent changes of significance should be marked. In those cases where there are many features in the vicinity of the port for which information is required, the use of a tabular form referring to points marked on the map may be appropriate.

b. A scaled plan of the port should be provided to show:-

(i) the route through the port to be taken by explosives vehicles;

(ii) the locations in the port where explosives vehicles might be parked;

(iii) the locations in the port where explosives might be transferred between vehicles (eg between road vehicle and straddle carrier);

(iv) the locations in the port where explosives might be temporarily stored, including the locations where explosives may be moved in the event of an emergency;

(v) the locations in the port where explosives are to be transferred from ship to shore or *vice versa*;

(vi) the locations in the port where other dangerous goods might be present, including the types of goods and an estimate of the quantities present;

(vii) the locations of people within the assessment area.

For this purpose a larger scale map would be necessary, as would a specific annotation to show the required features.

c. A full account should be given of procedures for moving explosives through the port from the point of entry to the point of departure. The account should specify:-

(i) the modes of transport to be used - road vehicle, tractor, straddle carrier, rail vehicle etc;

(ii) the quantity and nature of explosives transported on each vehicle;

(iii) the number of vehicles to be moved through the port, and whether these are to be moved separately or in convoys;

(iv) the type of any inter-modal transfer;

(v) the ship to shore (or shore to ship) mode of transfer - roll-on roll-off (RoRo), container lift, lightering, break-bulk handling;

(vi) the procedures to be followed in an emergency, including the procedures to be followed in the event of an explosives load being suspected of being in an unsafe condition.

d. An estimate of the number of persons on site and how they are distributed throughout the port. As well as port employees estimates should be made of visitors, including delivery staff, clients, customers and contractors.

All of this information is vital to the analysis as clearly accident probabilities will in part be a function of the types of handling procedures employed in the port, and the consequences of explosives accidents will in part be a function of the population distribution in and around the port.

3 Information relating to Management Systems

a. A full account should be given of systems for monitoring the movement of explosives through the port and for controlling the safe operation of these movements. The account should specify:-

(i) the personnel responsible for logging the arrival of explosives into the port;

(ii) the personnel responsible for issuing directions/instructions to drivers of explosives vehicles;

(iii) the personnel responsible for locating explosives vehicles in the event of an emergency; in addition information is needed on how to recognise, and the procedures to be followed in the event of, an emergency.

It would be important for the applicant to specify clearly the conditions and procedures under which explosives would be moved through the port. Any license granted to the port operator would only be valid for the conditions and procedures specified in the application - as clearly any changes in conditions and procedures could have some bearing on accident probabilities and consequences. It is suggested that the license would relate to the operating conditions specified in the application - and indeed would fix these conditions by specific reference to the application.

4 Information relating to the Potential Major Accidents

The applicant's safety case in covering items 1, 2 and 3 above would have identified the potential for the consequences of accidents arising from the handling of explosives. This is a necessary stage but by itself unlikely to be sufficient demonstration that it is reasonable, on safety grounds, to increase the license limits which are based primarily on a consequence based assessment. It can be argued that any increase in license limits constitutes an increase in risk. It is therefore necessary to make a convincing argument that the risk increment is overall or on balance negligible, taking account of the risk exposure of the workforce and public. It may also be relevant to compare a risk increment with some corresponding benefit in order to put it into a broader context.

As a result it is clear that the magnitude of the risk has to be estimated in order to make such an argument. Therefore, the information in items 1, 2 and 3 must be supplemented by formal and quantified consideration of potential major accidents.

The applicant's written submission in support of a higher license limit therefore would need to detail the work undertaken for each of the four stages that comprise the classical form of the QRA procedure:

Accident identification analysis - in which potential causes of explosives accidents in ports would be identified.

Accident frequency analysis - in which estimates would be derived for the potential frequency of occurrence of the identified accidents.

Accident consequence analysis - in which an assessment would be made for the consequences which may be expected from the occurrence of explosives accidents.

Risk analysis - in which the results of the above three stages would be combined to produce estimates for individual and societal risk. In the present context individual risk would be expressed as the annual probability for a specified person being killed as a result of there being an explosives accident within a port, while societal risk would express the chance of such an accident causing a number of fatalities.

It is beyond the scope of the present paper to describe the methods and techniques by which each of the above four stages might be accomplished. Descriptions of appropriate methods of analysis can be found in a recently published report on the risks from the transportation of dangerous goods (including explosives) in the UK.[3] As noted previously, it is likely that considerable effort will be required to undertake the analysis.

It is suggested that the operator should consider two broad categories of accidental initiation of explosives material:-

a. Initiation caused by accidents imparting high levels of energetic stimuli to explosives, eg crane failures, vehicle collisions and fires, ship fires etc.

b. Initiation brought about by the presence of unsafe items in explosives loads. This type of initiation may occur without there being any precursor accident of the type mentioned above.

An important factor that will need to be addressed in any reasonable attempt at quantification of the potential frequency of occurrence of explosives events in ports is quantification of the conditional probability that an explosives item would initiate given the occurrence of an accident of the type listed in a. It is not certain that there are currently sufficient data available to allow objective quantification of probability values for all different types of explosives items given the occurrence of the different types of foreseeable port accidents. There may be a need for fundamental research to be undertaken to clarify areas of uncertainty; it would certainly be desirable for trials to be undertaken to generate objective values for parameters, rather than for too much reliance to be placed on expert judgement.

In carrying out a consequence analysis to determine the numbers of casualties that may be expected from accidental initiations of explosives materials, it is suggested that the applicant should consider the effects of blast, fragments and heat. Ideally, the explosion effects models used by the applicant would take account of the effects of shielding provided by structural features typically found in ports, such as container stacks, and would also be sensitive to buildings of different types of construction. However, if the applicant does not have access to such detailed explosion effects models, it would be important for him to use models which are known to produce a conservative output, ie the analysis should overstate rather than understate potential numbers of casualties.

Finally the HSE will need to form some judgement on the tolerability of the risk levels estimated by the applicant. This may not be a problem in the case of individual risk for which there are some fairly well established criteria in the UK [4]: these are 10^{-3} and 10^{-4} per year for the risk of death to members of a workforce and the general public respectively; an individual risk that exceeded the appropriate value would be regarded as unacceptable. At the other end of the scale a risk below 10^{-7} per year could be regarded as negligible. Levels of individual risk falling between these boundaries would not normally be regarded as intolerable but would be required to be reduced to a level "as low as reasonably practicable". However, numerical criteria can only be used to guide decision makers; it is unlikely that such criteria will become enshrined in legislation. The criteria discussed apply to people already at risk from hazardous installations; different criteria may well apply to the introduction of new risks or new populations. Cost-benefit analysis would be required to determine which risk reduction measures might be regarded as reasonably practicable.

The application of numerical acceptance criteria to societal risk remains to be fully resolved in the UK, though some progress has recently been made[3]. It is beyond the scope of this paper to enter into a discussion on the difficulties encountered in attempts at defining societal risk criteria for activities involving explosives, though clearly such criteria will be needed if a risk-based approach to explosives licensing is to be introduced. It is expected that criteria for operations involving explosives will be considered further during the course of a study recently commenced by the Health and Safety Commission's Advisory Committee on Dangerous Substances into the risks from the handling of explosives in ports.

WHAT ARE THE ADVANTAGES OF THE QRA APPROACH?

The present QD approach to licensing is primarily one of hazard control, ie it effectively limits the consequences of potential accidents (which are perceived to have a low probability of occurrence). The main drawback of this approach is that in some situations it may, at considerable economic cost, do no more than safeguard small numbers of people against an event that is very unlikely to happen. This may be particularly true in the case of any port handling only insensitive explosives; the present system does not discriminate between sensitive and insensitive explosives substances. A QRA-based approach to licensing would essentially differ from the QD approach in that it would set explosives limits based on risk rather than just the consequences to be expected from explosives accidents. In other words the license would take account of the likelihood of an explosives accident occurring as well as the numbers of fatalities expected from such an accident. The major advantage to the port operator is likely to be higher limits for those explosives which are relatively insensitive to energetic stimuli - ie because of the low expected initiation frequency. A QRA-based approach to licensing would also offer a number of more general advantages, including:-

a. General increase in awareness by port operators of risk-generating activities.

b. Identification of high risk operations with scope for safety improvements through site specific measures.

c. Better understanding of risks from potential interactions of explosives with other types of hazardous cargoes in the port.

d. Identification of significant risks for particular modes of handling (eg type of lifting crane/handling operation) with possible long term solutions and subsequent reductions in risk.

e. Scope for higher explosives limits when specific conditions prevail.

WHAT ARE THE DISADVANTAGES OF THE QRA APPROACH?

There are a number of potential problems associated with QRA-based approaches to licensing. These problems can be conveniently summarised under two headings: technical shortcomings and administrative drawbacks. The major technical shortcomings are:-

a. The uncertainty inherent in the results of the QRA process. This uncertainty stems from many sources, including doubts about whether all potentially significant causes of accidents have been identified, questions over the appropriateness of data used to estimate accident probabilities and the inaccuracies of models used to predict the consequences of accidents (the same inaccuracies exist in any assessment based on the QD approach). In many cases probability estimates need to be derived for accidents for which there is little or no historical experience, and in such cases analysis is required of all possible causes of the accidents in question - some of which can be extremely complex in nature - and probability estimates necessarily synthesised using "near miss" data and expert opinion.

b. The assessment of human error presents particular difficulties. It is important that human error be taken into account as a potential cause of accidents if the results of a QRA are to be complete. The HSE has noted that human error may be considered implicitly or explicitly. In the former case overall accident rates would be used in the analysis, the assumption being that these rates have been derived from data for all causes of accidents, including human error. In the latter case a separate analysis would be made of the potential causes of human failure. The implicit approach produces risk estimates relating to an average level of human error; but the quality of safety management at ports may vary. This raises the question of whether adjustment factors should be applied to accident rates to reflect the quality of safety management. The

HSE's present view is that any allowance for good management should only be applied, if at all, within narrow limits[5].

c. Different risk analysts may produce different estimates of risk for the same port, reflecting different depths of analysis undertaken and, perhaps, different levels of knowledge and expertise among the risk analysts. Clearly it could be of mutual benefit for the industry to agree with the HSE an acceptable methodology. The establishment of an agreed methodology would most likely encourage a move towards the use of QRA in the field of explosives, but may not sit comfortably with an overall intent to introduce a goal setting approach to safety as distinct from one which relies on prescription, whether mutually agreed or otherwise.

The major administrative drawbacks are:

d. Compared to the present QD system of licensing, a QRA-based system would be time-consuming and consequently costly. It is likely that considerable expertise and effort would be required to prepare and to evaluate an application submitted by a port operator; further effort would then be required to issue the license, which would need to specify clearly (via reference to the applicant's QRA report) the precise site-specific operating conditions under which explosives are to be moved through the port.

e. Due to the sensitivity of risk levels to changes both on and off site, it is further considered that the license would need to state clearly when changes in operating conditions, procedures and developments in the vicinity of the port would be of such significance as to require further assessment to be undertaken.

f. It may be necessary to establish new consultation zones based on risk contours; an increase in the area of the consultation zone around the port may result in increased numbers of consultations.

g. Subsequent encroachment or changes in operational circumstances could result in relatively frequent reassessments and amendments to ports licenses.

h. Port operators may have difficulty in understanding the terms of a QRA-based license and the factors calling for reassessment. There may thus be a requirement for frequent inspections/safety audits to ensure compliance with the conditions of the license.

i. All of this has cost implications. Under the existing system charges are made for an inspector's time against the cost of the license; these costs would clearly increase for QRA-based licenses.

SUMMARY

The system of ports explosives licensing presently employed in Great Britain is based primarily on hazard limitation, ie restrictions are placed on the quantities of different types of explosives that may be moved through ports so as to ensure limited consequences in the event of an accident. The use of QRA in support of safety cases for installations where large quantities of flammable and toxic materials are handled is now well established in the UK.

This paper has outlined one way in which a risk-based approach to ports explosives licensing could be introduced. The advantage of such a system for port operators is likely to be higher license limits for those explosives which are relatively insensitive to energetic stimuli; it is also likely that such a system would lead to a greater awareness of risk generating activities within ports. However, there are also a number of both technical and administrative drawbacks to such a system. In the UK it remains to be decided whether the advantages of a risk-based approach to licensing are sufficient to outweigh the disadvantages. The final decision on such license applications would be socio-political, based on the technical considerations.

DISCLAIMER

Opinions expressed are those of the authors and should not be considered as statements of HSE policy

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RISKS FROM THE TRANSPORT OF EXPLOSIVES

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SUMMARY

1. A recent study and report [1] on the major hazard aspects of the transport of dangerous substances has made an importance contribution to the development of QRA methodologies and criteria for assessing the risks involved in the movement of explosives articles and substances.

2. Some of the key issues are discussed in looking ahead at the extension of the study from road and rail transport to the risks from explosives in ports. See also R Merrifield/P A Moreton this seminar.

3. The programme to license the ports and harbours around the coastline of Great Britain which handle military and commercial explosives [2] is now completed. It has generally led to significant reductions in the amounts of explosives which may be handled. This reflects the scale of redevelopment in and around ports but also challenges the validity of established QD relationships as the proper basis for assessment.

4. Reduced ports limits also pose problems back up the logistical chain which may need to be taken into account in the overall safety equation. QRA cannot itself provide the answer but will inform the judgemental process.

ACDS STUDY OF MAJOR HAZARDS IN TRANSPORT

5. The so-called ACDS study, completed for the Health and Safety Commission under its Advisory Committee on Dangerous Substances, embraced the quantified risk

assessment (QRA) of the road and rail transport of chlorine, ammonia, liquified petroleum gas and motor spirit, the road and rail transport of explosives substances and articles, as well as the ports risks for handling of non-explosive substances in bulk.

6. The Report [1] describes and discusses in some detail the methods used and sets out the findings and recommendations which emerged. It argues that the principal risks in the transport of dangerous substances have been evaluated sufficiently for conclusions to be drawn about the overall national situation. It also makes suggestions on ways to reduce risks to 'as low as is reasonably practicable' (ALARP) and methods for that assessment. None of the risks studied were judged intolerable but on the other hand few could be regarded as negligible.

7. Criteria developed to judge the tolerability of individual and societal risks adds a further dimension to the debate prompted by earlier publications [3] [4] [5].

8. Foremost amongst other findings reported is the importance of management in minimising risks by providing, promoting and maintaining safety systems and standards [6] [7].

ROAD AND RAIL TRANSPORT OF EXPLOSIVES

9. Not surprisingly given the many different types and load sizes of explosives, the method of assessment proved much more elaborate than for other substances studied. There was some read-across, for example of the method used to calculate population densities along routes or in the application of risk criteria. But a number of techniques were used to bring the study of explosives within manageable proportions and which could have wider application and interest.

10. In summarising the main stages of the assessment process in the following paragraphs, the aim has been to highlight some of those techniques.

CATEGORISATION OF EXPLOSIVES

11. An important part of the methodology for assessing rates of occurrence for different types and sizes of explosives events was the categorisation of explosives into just seven groups. All explosives in a particular group could then be treated as if equally vulnerable to initiating stimuli and produce similar effects if initiated.

12. Data on rail and road explosives traffic could then provide two initial outputs; estimates of overall annual traffic volumes and estimates of the relative proportions of the various categories of explosives moved.

TABLE 1

H.D	CATEGORY	RAIL WAGONS	ROAD VEHICLES
		2.6 X 10 6 Km/yr	4 X 10 6 Km/yr
		%	%
1.1	'M'	0	51
	'N'	16	23
	'P'	11	20
1.2	'Q'	17	2
1.3	'R'	0	3
	'T'	12	1
1.4	'W'	44	N/R

M - heat sensitive substance in flammable packaging
N - heat sensitive article - not readily ignitable
P - heat sensitive substance
Q - heat sensitive article
R - heat sensitive substance in flammable packaging
T - heat sensitive substance or article in on-flammable packaging
W - heat sensitive article but no great hazard

No H.D 1.5 or 1.6 movements in UK. Fireworks not included.

13. There are significant differences between rail and road traffic patterns. Virtually all rail traffic is military and includes no more than 27% of H.D 1.1; half insensitive to heat and half not readily ignitable. Road traffic on the other hand includes up to 94% of H.D 1.1; over half heat sensitive substances in flammable packagings, a reflection of the commercial sector.

FREQUENCY OF INITIATING EVENTS

14. Studies of the historical accident record for explosives traffic over the last 40 years suggested that fire or the presence of unsafe material are the two most likely causes of explosives events on rail and road vehicles. Unsafe in that sense meaning an explosive badly packaged, manufactured or otherwise out of specification or in breach of legal requirements. A number of crashes or collisions of vehicles had been recorded but in no case had that led to an explosives event; impact was however considered in the study.

15. The rates for dangerous occurrences involving fire or impact were deduced from the historical data or when necessary from fault tree analysis. FTA for example resolved the problem that rail wagon and road vehicle technology had improved since the one fire recorded for rail (axlebox) or the four recorded for road (various vehicle defects). A combination of accident data, trials data and expert judgement provided the conditional probabilities that an explosives event would result from a fire or impact accident.

16. The historical occurrence of events involving the initiation of unsafe explosives was used directly, on the assumption that management standards would at least remain constant over time.

17. There had, over the 40 year period, been one event due to unsafe explosives on the railway, one on the roads. The latter tragically leading to the death of a fire-fighter, the only fatal explosives transport accident in that time [6].

18. The derived frequency rates:

TABLE 2

Initiating Mechanism	Rate of Occurrences of Explosives Events	
	Rail: Wagon - Km^{-1}	Road:Vehicle - Km^{-1}
Unsafe Explosives	1×10^{-9}	1×10^{-9}
Fire	6×10^{-10}	2×10^{-9}
Impact	1×10^{-10}	2×10^{-10}

19. Initiation of unsafe material is significant for both modes, indeed considered - in view of the accident

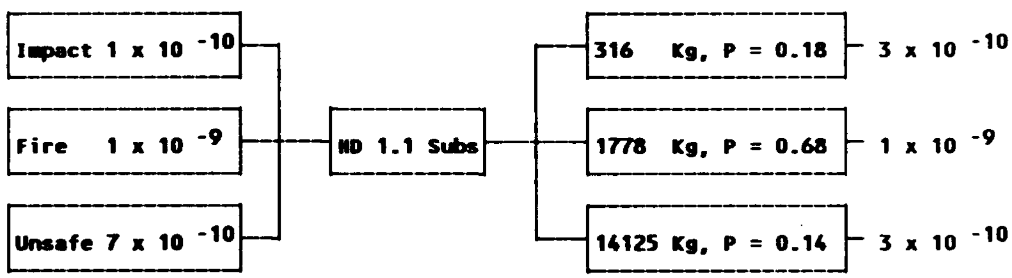
record for explosives storage - to be one of the more probable causes of an event. The rate for fire-induced events is slightly higher for road than rail. On road vehicles, tyre fires were judged to be the major source of ignition.

PARTITIONING OF EXPLOSIVES EVENTS

20. Because the consequences of an event on the road or rail would depend on both the type of explosive carried and on the quantity of explosives in the load, it was necessary to partition events to obtain a series of frequency rates which took both factors into account. This involved a complex plan of event trees and the input of data on representative load sizes obtained by maximum entropy analysis.

21. Use of that technique, resolved the practical problem that fatality estimates could not be calculated for all sizes of explosives loads transported by road and rail. The grouping of loads into a smaller number of notional sizes of cargo, like the grouping of explosives into categories, kept the study within manageable proportions.

22. An extract from an event tree outlining possible types and sizes of explosives events on road vehicles will illustrate the process. This shows the three nominal load sizes derived for substances of H.D 1.1 and the proportion of the overall mileage (P) each accrued. A total of 11 load sizes and corresponding rates of initiation were generated for road transport.



HAZARD RANGES

23. Hazard ranges to 90%, 50%, 10% and 5% fatalities for each of the representative explosives loads moved by road and rail were calculated by reference to appropriate consequence models:

- HD 1.1 effects were embraced by an analysis of twelve war-time V2 rocket attacks;

- HD 1.2 effects were based on worst case trials data, but limited to 50 Kg NEQ;

- HD 1.3 effects were judged from available models for idealised and non-idealised fires.

24. The models undoubtedly introduced a number of uncertainties well recognised in the Report but the derived results were judged somewhat conservative in the context of a road or rail incident.

25. The hazard ranges as derived were limited in practice to about 87m, though fatalities could extend out to about 107m in an event involving communication between fully loaded rail wagons. It is however axiomatic that much wider injury and damage can result; the normal public evacuation distances for 16 te and 5 te of HD 1.1 explosives - regulatory limits for different kinds of road vehicle - are set at 560m and 380m respectively.

Population Densities

26. The numbers of people encompassed by the hazard ranges from the representation loads depended on three factors:

a) the extent of alongside clear zones, typically 25m for rail, 27.8m for motorways, 10m for dual carriageways, zero for single roads;

b) the density of alongside populations - urban 4210, surburban 1310, built-up rural 210 or rural 20 people per square kilometre;

c) the proximity of other route users - on rail in a passing passenger train, on road the build-up behind an explosives vehicle accident and the slowing down of traffic on the opposite side.

Risk Analysis

27. Estimates of the overall national risks from rail and road transport were made by reference to selected routes having the features which characterise routes generally. Two rail routes were chosen to reflect the different patterns of traffic on inter-city mainlines and on provincial and freight lines. The one road route included all three classes of road and went through both urban and rural areas.

28. The representative routes were first partitioned into the various sections which properly reflected the on-route and off-route population densities associated with them. By assuming that all of the national explosives

traffic passes in turn through each section, the frequencies with which different types of explosives events might occur and the corresponding fatality levels could be estimated. In the case of the road study this generated 308 f/n pairs; from 28 road sections and 11 load sizes.

29. Computation of f/n pairs provided overall frequencies of events leading to different numbers of fatalities in the bands considered:

Frequency of N or more Fatalities (yr^{-1})				
	N = 1	N = 3	N = 10	N = 30
Road	$1x10^{-2}$	$1x10^{-2}$	$7x10^{-3}$	$4x10^{-4}$
Rail-mainline route	$6x10^{-4}$	$3x10^{-4}$	$1x10^{-4}$	$2x10^{-6}$
Rail-provincial route	$7x10^{-4}$	$4x10^{-4}$	$2x10^{-4}$	$1x10^{-6}$

30. It was concluded after comparing those results with criteria developed as part of the wider study, and after taking into account the various uncertainties, that the national societal risks of transporting explosives by road and by rail are not intolerable but are at a level where they require reduction. En-route *individual risks* are considered minimal, though the risks at specific locations where they may be concentrated, such as at a rail marshalling yard with a high throughput and nearby population may require more detailed study.

31. Although the societal risks estimated for the rail transport of explosives were significantly lower than those for road, no conclusion could be drawn about the relative safety of the two modes; too many differences were revealed. The risks to off-road and off-rail populations were broadly similar. The predominant risk of road transport is that to other road users.

32. Risk reduction measures suggested by the study included:

- better fire protection of load-carrying compartments on vehicles, in particular from tyre fires;
- active and passive systems to prevent spread of fire inside load carrying compartments;
- phasing out of NG-based blasting explosives;
- use of non-flammable dunnage in rail wagons;

- use of rail barrier wagons to prevent communication;

- detailed study of any marshalling yard with a large throughput of explosives and a nearby population;

- continued double-manning of explosives vehicles.

33. The final caution; estimates of risk should be used with care and not be taken out of the context of the study.

RISK CRITERIA

34. It is outside the scope of this paper to set out a properly balanced discussion of risk criteria that might be appropriate in the explosives field or to make all of the necessary qualifications. The purpose here is merely to indicate in very broad terms some of the principles applied in the ACDS Report (1) and on which judgements about the tolerability of estimated risks were made.

35. Criteria for levels of risk for the transport of dangerous substances were developed within the conceptual framework of:

- intolerable, risks so high as to be socially and politically unacceptable regardless of any benefit that may accrue from them. Such risks call for immediate action to reduce them, irrespective of cost;

- negligible, risks so small that they do not require action to be taken to reduce them;

- ALARP, risks which fall into a band between the above two levels. Such risks though broadly tolerable should be reduced to a level that is 'as low as reasonably practicable' - the greater the risk, the greater the cost of reduction justified.

INDIVIDUAL RISK

36. The risks to individuals living or working in the vicinity of fixed locations such as railway marshalling yards, lorry stop-overs and ports were judged against:

- a risk of death of 10^{-3} or 10^{-4} per year for workpeople and the public, respectively, as intolerable;

- a risk of death of 10^{-6} as broadly acceptable and of 10^{-7} as truly negligible;

as levels relevant to existing risks to existing populations. Different criteria may be appropriate for the introduction of new risks to an existing population or an increase in population subject to an existing risk.

37. Individual risk was also used as a surrogate for societal risk, in particular to discuss the questions which arise in relation to land development for housing near to a fixed location. In essence, upper limits are set for the risk to an individual of receiving a <u>dangerous dose</u> of an effect such as over-pressure, one which could cause:

- severe distress to almost everyone;
- medical attention for a substantial fraction of those exposed;
- serious injury, requiring prolonged treatment to some;
- death to any highly susceptible person.

38. The ACDS report roughly equated a 5% chance of death due to explosion effects to a dangerous dose in the event of an accident. The frequency with which any population at the 5% fatality hazard range would be exposed to a dangerous dose of blast over-pressure, say, is then equal to 20 times their individual risk of death. It would be unlikely to advise against a new housing development providing for about 25 people where the calculated individual risk of receiving a dangerous dose is less than 10^{-5} per year. But concern would be expressed about new developments for more than about 75 people if the individual risk of receiving a dangerous dose exceeded 10^{-6} per year. (Reference 4 suggests this corresponding to a risk of death at about 3×10^{-7} per year).

Societal Risks

39. ACDS noted the difficulties in determining universally relevant levels of tolerable and negligible societal risk and the many qualifications it is necessary to make. But during transport itself, the risks to any particular individual are much more transient and so less relevant than criteria for risk to the public in general.

40. The proposed societal risk criteria were based on the observation that risks at Canvey Island, in the south of England, were judged just tolerable after the most

searching technical and socio-political assessment. The risks there were seen as similar enough in nature to the risks in transport to allow this limited degree of read across, though some questions were raised about additional aversion factors in particular with respect to explosives.

41. A pair of parallel lines on an FN graph, with a slope of minus one were proposed as criteria for 'tolerable' and 'negligible' in one locality. The upper 'just intolerable' line passes through the 'Canvey point' (N> 500, $F = 2 \times 10^{-4}$ per year). The lower line corresponds to a predicted frequency a thousand times lower. Risks below this are regarded as negligible. Risks above the upper line are intolerable if concentrated in any one locality. Risks between the lines should be reduced so far as is reasonably practicable.

42. The problem inherent in comparing estimates of national societal risk against the local intolerability criteria were not fully resolved. But proposals were made for a 'national scrutiny level' of societal risk, determined by scaling up the tolerable risk per tonne of cargo handled at Canvey by the national volume of trade, and expressed as a further parallel line on the F/N graph. If national risk approaches this level it will not necessarily be intolerable, but should be looked at with special scrutiny.

43. A 'local scrutiny level' for societal risk at a particular fixed location, like a port, can be derived in a similar way; scaling in this case by the volume of trade at the port rather than the national volume. The level only has meaning if it falls below the local intolerability line referenced to Canvey.

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RISK ANALYSIS FOR TEMPORARY STORAGE OF AMMUNITION IN COMBAT AREAS

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by

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Many elements of the Army must store quantities of ammunition and other explosives in order to perform their basic mission. Department of Defense (DOD) regulations provide safety standards to minimize the risk and consequences of an accidental explosion of stored ammunition (Reference 1). For operations in combat areas, the standards are less restrictive, and allow reduced separation distances (Quantity-Distance, or Q-D's) between the ammunition storage and personnel, structures, vehicles, or other assets. Furthermore, a unit commander may determine that even those allowable reductions in Q-D's cannot be met without adversely affecting his unit's combat readiness.

To make the most intelligent decision, the field commander must weigh the increase in risk to his troops and equipment that would be created by compromising the safety standards, against the tactical benefits to be gained. At present, there is no ready reference guide to help the commander make such an "on-the-spot" judgement. The purpose of this study is to develop realistic, practical, and applicable guidelines for field commanders which will describe, in tangible, quantitative terms, the increased risk incurred by specific deviations from the prescribed ammunition storage safety standards (i.e., the Q-D values) in combat scenarios.

PROBLEM DEFINITION

The problem may be described by the example shown in Figure 1. Items A and B are storage units of ammunition (open stacks, truckloads, etc.) and Item T is a "target" that is vulnerable to explosion hazards. Given an explosion at A, P_A is the probability that a target T is damaged (or in the case of personnel, injured) by an explosion at A. P_B is the probability of damage or injury to target T by the effects of an explosion at B. $P_{B|A}$ is the probability that an explosion at A causes B to sympathetically detonate. The problem of compounded probabilities is simplified by the fact that, although the detonation of B is dependent on the detonation of A, the hazardous effects (particularly fragmentation, which is the

main focus of this study) may be considered as independent events. Statistically, this means that the probability of damage from each event can be determined independently and then combined. The solution to the problem is based on a "favorable outcome," which in this case is the probability of not getting hit, or survival. Survival for A is expressed as $P_{SA} = 1 - P_A$, and for B as $P_{SB} = 1 - P_B$. For the simple case where both A and B explode, the probability of a "hit" at T is expressed as:

$$P_T = 1 - P_{S(A\&B)} = 1 - (1 - P_A) * (1 - P_B)$$

Notice that $P_T = 0$ when P_A and $P_B = 0$, and $P_T = 1$ when P_A and $P_B = 1$. $P_T = 0.75$ when P_A and $P_B = 0.5$.

In the above example, it was assumed that storage units A and B both explode. This is based on the conditional probability $P_{B|A}$ (that B will explode, given an explosion at A). Here the "favorable outcome" relates to the probability that the detonation of A will also cause a sympathetic detonation of B. The conditional probability, if P_A is not 0, may be expressed as $P_A * P_{B|A}$ (reference 2). Thus:

$$P_T = 1 - (1 - P_A) (1 - P_A * P_{B|A})$$

Given these relationships, all that remains is to determine the individual probabilities.

EXPLOSION EFFECTS

The possible causes for sympathetic detonation of a second ammo stack are airblast, fragment impact, and slow cook-off of ammunition due to fire (caused by fire-brands thrown by the initial explosion). The probability of damage or injury to a target stems from two sources - airblast and fragments/debris from the explosion(s).

Recent tests indicate that airblast is probably not a direct factor in sympathetic detonation of individual ammo stacks. Also, airblast can be easily predicted for a known net explosive weight (NEW), which represents a "worst case" scenario - the mass detonation of the entire stack. Therefore this study concentrates on the fragment hazard.

COMPUTER MODELING

The Q-D Fragment Hazard (FRAGHAZ) Computer Program, developed by the U.S. Naval Surface Warfare Center, was used to address the fragment hazard in this analysis. FRAGHAZ (Reference 3) employs fragment data obtained from small-scale tests that represented large stacks of munitions. Among the data sets available for use in the program are those for MK-82 GP bombs and 155mm projectiles. To determine the hazard to a specified target, complete trajectories are calculated for each fragment identified in the small-scale test data set, using random variables to determine the hazard to a specified target. A number of Monte Carlo simulations (usually 60) are run to statistically evaluate a given problem. The program's output is in the form of fragment densities and probabilities of target hits.

Because of the many types of ammo used by the military, a worst case donor munition (for fragmentation purposes) was chosen. The general consensus in the explosive safety community was that, for this study, a representative worst case munition is the Comp B-filled M107 155-mm projectile.

DAMAGE CRITERIA

Since this study deals with temporary encampments in combat areas, the main concern is with hazards to personnel, rather than damage to permanent buildings. The DOD standards define a hazard criterion of one hazardous fragment impact per 56 square meters. Since the FRAGHAZ program calculates statistically for a number of simulations, and we must have some reference, we chose the 90 percentile statistic, which is also used in the DOD standard. Also, the Q-D's defined by the standards are based on the acceptance of some small degree of risk - specifically, a one percent probability of a hit. This number was used here in determining an acceptable probability of injury.

The remaining problem is to define a hazardous fragment. Previously this had been accepted as a fragment with an energy of 79 joules (58 ft-lb) or more. Recently, however, the standards consider skin penetration as an injury criterion, and this has been incorporated into the FRAGHAZ program (reference 4). For 155mm projectiles in the situations considered in this study, comparisons showed no measurable difference for calculations made using the skin penetration criteria than for those using the 79-joule criteria.

STORAGE METHODS

The fact that this analysis is concerned only with the field storage limits the number of ammo storage methods that need to be considered. The storage

methods that would most likely be used at a temporary field site are uploaded trucks or ammo stacked on the ground surface. At the recommendation of the U.S. Army Technical Center for Explosives Safety, the Palletized Load System (PLS) was considered as the method of storage. Several possible PLS configurations are shown in Figure 2. In some cases, barricades may be constructed between ammo trucks or munition stacks, or the trucks could be parked in trenches (either covered or uncovered), both to prevent sympathetic detonations of stacks by fragments from an accidental detonation of an adjacent stack, as well as to reduce the hazards to nearby personnel from such a detonation. The above conditions dictate several factors that can influence the probabilities of a fragment hit on a target:

(1) Standoff height of the ammo stack above ground level (either pallet height or height of a truck body).

(2) Number of stacked layers (tiers) of ammo.

(3) Total number of projectiles in a stack.

(4) Use of barricades between stacks.

The FRAGHAZ calculations indicated that, for all practical purposes, the standoff height of a stack (Figure 3) and the number of tiers in a stack (Figure 4) have no effect on fragment hazard. The main factor defining the fragment hazard is the number of projectiles (Figure 5) on the face of the stack, which can be equated to a unique NEW (less than the NEW of the entire stack) by assuming that the stacks contain PLS loads.

The FRAGHAZ program has been adapted to evaluate the influence of barricades (reference 5). Figure 6 shows the results of a FRAGHAZ calculation, which indicate the extent that the fragment hazard can be reduced by the use of barricades. Notice that, at far distances, a sloped barricade (45 degrees) provides less reduction in the probability of hit than a vertical-faced barricade, but the risk is still well below the acceptable limit. These calculations are based on the assumption that fragments are stopped by the barricades or, in the case of the sloped barricades, may ricochet off and be deflected upward at a steeper trajectory angle, thus accounting for the higher hit probabilities at ranges beyond 270 meters. Barricades are known to suppress fragment dispersion. However, although these calculations are believed to be relatively accurate, there is not sufficient data available to verify the calculation results.

INCREASE IN RISK

If we define Q-D's based on the one percent probability of a hit as calculated by FRAGHAZ, the information presented in Figure 5 may be displayed as increased risk vs. percent reduction in Q-D (Figure 7). Figure 8 shows the increased risk vs. percent reduction in Q-D using the Q-D's recommended in Chapter 10 of the DOD Ammunition and Explosives Safety Standards as departure points. Table 1 summarizes the increase in risk due to Q-D violations for open storage of ammo in a theater of operations.

Determining the probability of sympathetic detonation of a second ammo stack by the explosion of a nearby stack is a much more difficult problem. There has been much discussion recently in the explosives safety community about selection of a "worst case" acceptor munition (i.e., one that is most susceptible to detonation by a fragment impact). Unfortunately, the most probable candidate is considered too dangerous to test in the detail required. Therefore many assumptions are necessary to investigate this portion of the problem. It appears that the main factors affecting the probability of a detonation due to a fragment impact are the fragment mass and impact velocity. However, many other factors - e.g., fragment shape, impact angle, fragment temperature, whether the fragment penetrates the target or not - all contribute to the possibility of causing detonation.

The FRAGHAZ program is designed to predict the probability that a fragment with a certain kinetic energy will hit a given target at some distance from an explosion. Since we do not have the data necessary to determine the energy required to cause a detonation by an impact, Figure 9 shows the probability of a target (in this case a PLS ammo stack) being hit by fragments having a range of energy levels. Curve 1 in Figure 9 shows the probability of a hit vs. distance for all fragments. Curve 2 shows the probability of a hit by a fragment with a kinetic energy of 1500 joules (1100 ft-lbs) or greater. Curve 3 is for fragments with a kinetic energy of 7450 joules (5500 ft-lbs) or greater. The calculations indicate that the larger, high-energy fragments are only found at the closer ranges. Curve 4 shows the effects of a barricade on the probability of hit for all fragments. The calculations indicate a near-zero hit probability for high-energy (71,500 joules) fragments, implying that a barricade can be very effective in reducing the risk of sympathetic detonations of adjacent stacks. Recent tests (Reference 6) have confirmed that a properly constructed barricade can prevent a sympathetic detonation of a nearby ammo stack.

Another factor complicating the problem is that distances between stacks or parked uploaded trucks may be much closer than the FRAGHAZ program is currently set up to handle. However, as more information becomes available, and the problem becomes more clearly defined, modifications to FRAGHAZ should

allow this type of calculation, since fragment trajectories are calculated throughout their entire flight history. It is recommended that experimental data be collected to augment calculations of probability of detonation due to fragment impact.

SUMMARY

While not exhaustive in scope, the results of this analysis provide a useful indication of the increased risk to personnel incurred by violating prescribed Q-D's in theaters of operations. For example, decreasing the spacings between uploaded ammo trucks by 20 percent effectively doubles the risk of fragment injuries to personnel. A decrease of 30 percent causes the risk to increase by a factor of three. Additional analyses, along with verification by experimental data, should lead to comprehensive guidelines that may be incorporated in future revisions of the DOD standards.

ACKNOWLEDGEMENTS

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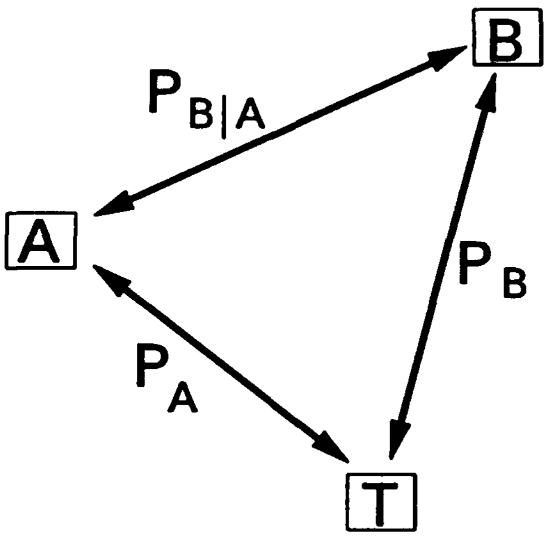

A & B ARE AMMO STACKS
T IS THE TARGET

P_A = PROBABILITY OF HIT AT T BY EXPLOSION AT A

P_B = PROBABILITY OF HIT AT T BY EXPLOSION AT B

$P_{B|A}$ = PROBABILITY OF EXPLOSION AT B DUE TO EXPLOSION AT A

FIGURE 1. PROBLEM DEFINITION

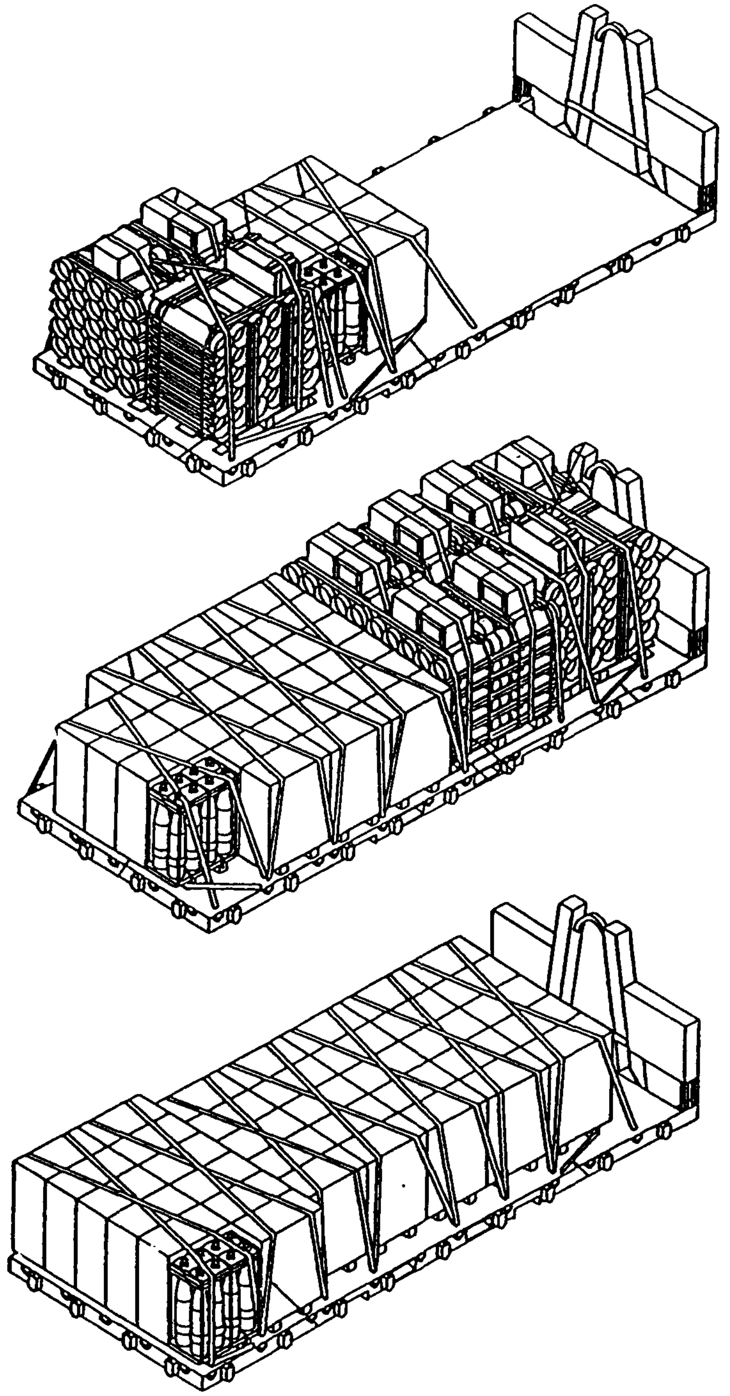

Figure 2. POSSIBLE PLS LOADING CONFIGURATIONS FOR 155 mm PROJECTILES

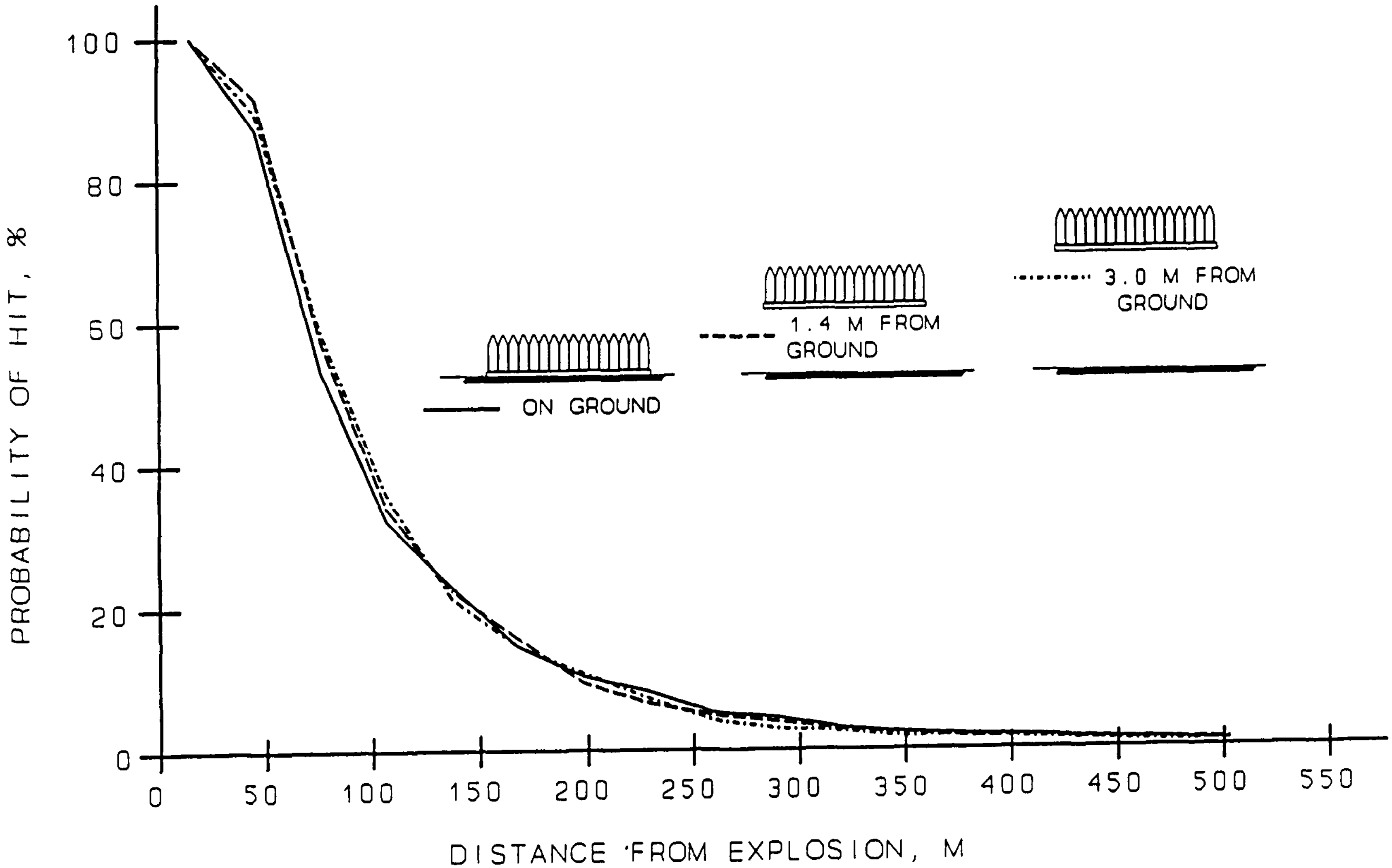

Figure 3. EFFECTS OF STANDOFF HEIGHT, 64 PROJECTILES

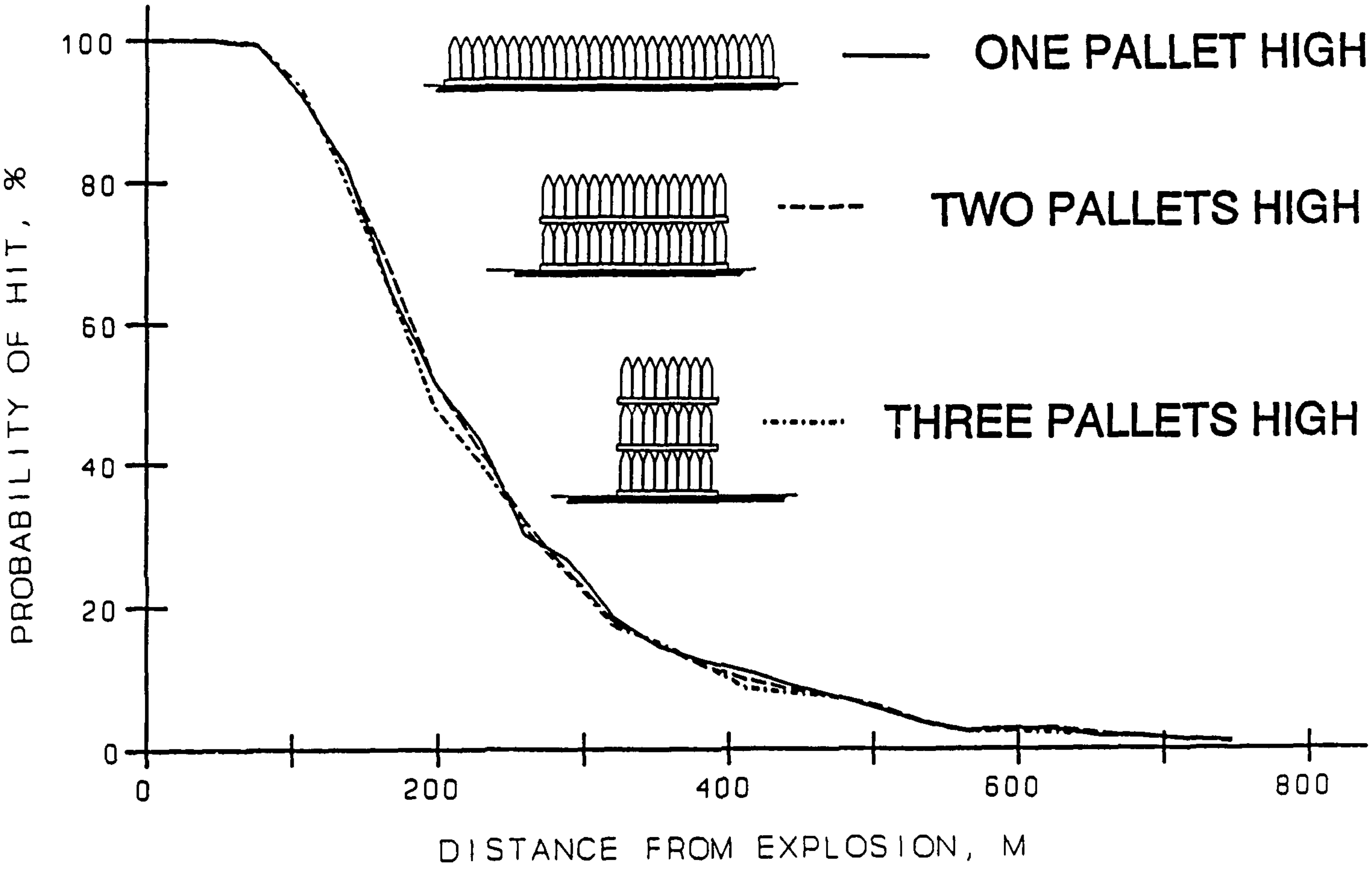

Figure 4. EFFECTS OF STACK CONFIGURATION, 100 PROJECTILES

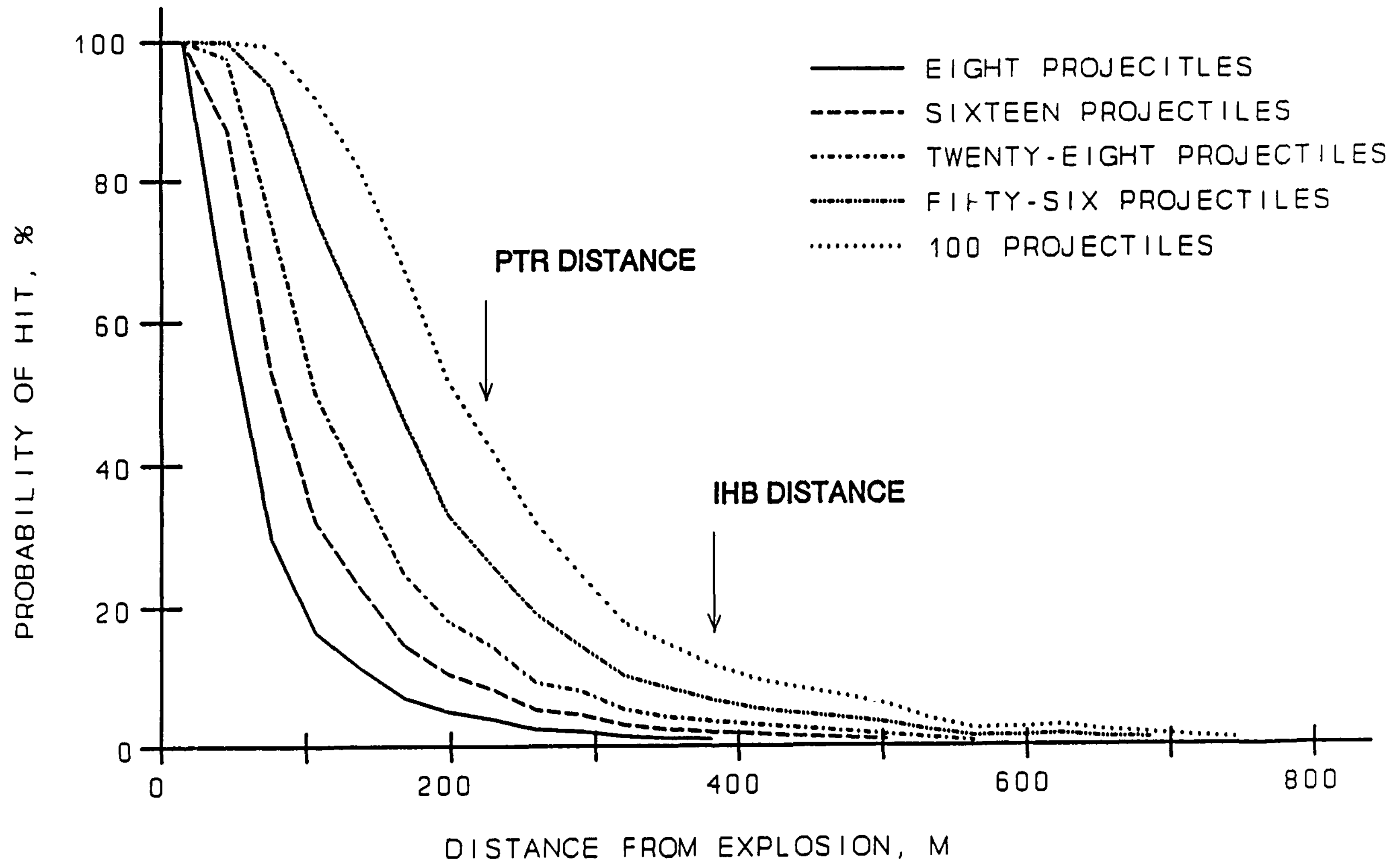

Figure 5. PROBABILITY OF FRAGMENT HIT ON STANDING MAN

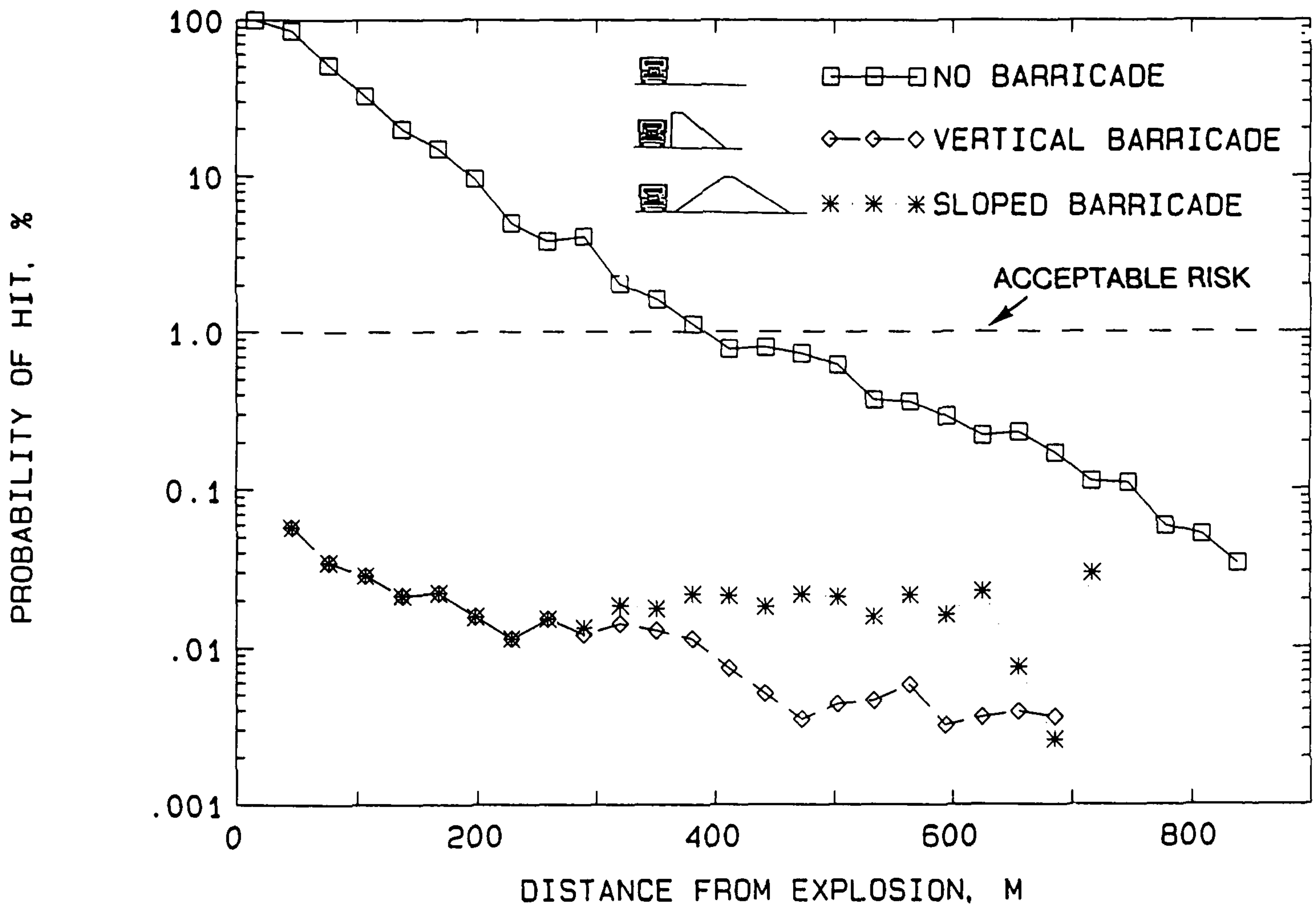

Figure 6. EFFECT OF BARRICADES ON HAZARD TO STANDING MAN (AMMO TRUCK DETONATION)

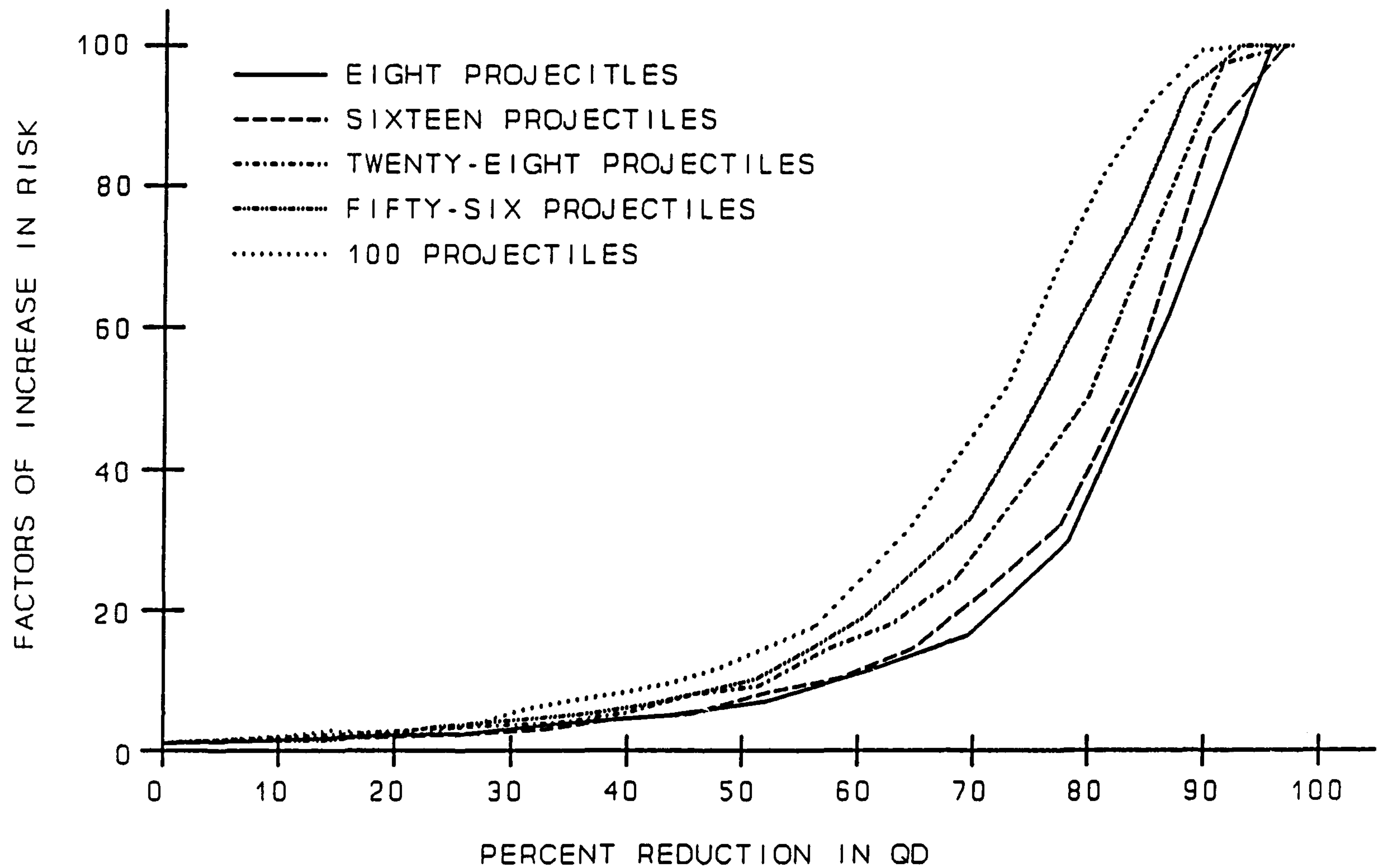

Figure 7. INCREASE IN RISK DUE TO REDUCTION IN CALCULATED QD's FROM 1% HIT PROBABILITY DISTANCE (FRAGHAZ PREDICTIONS)

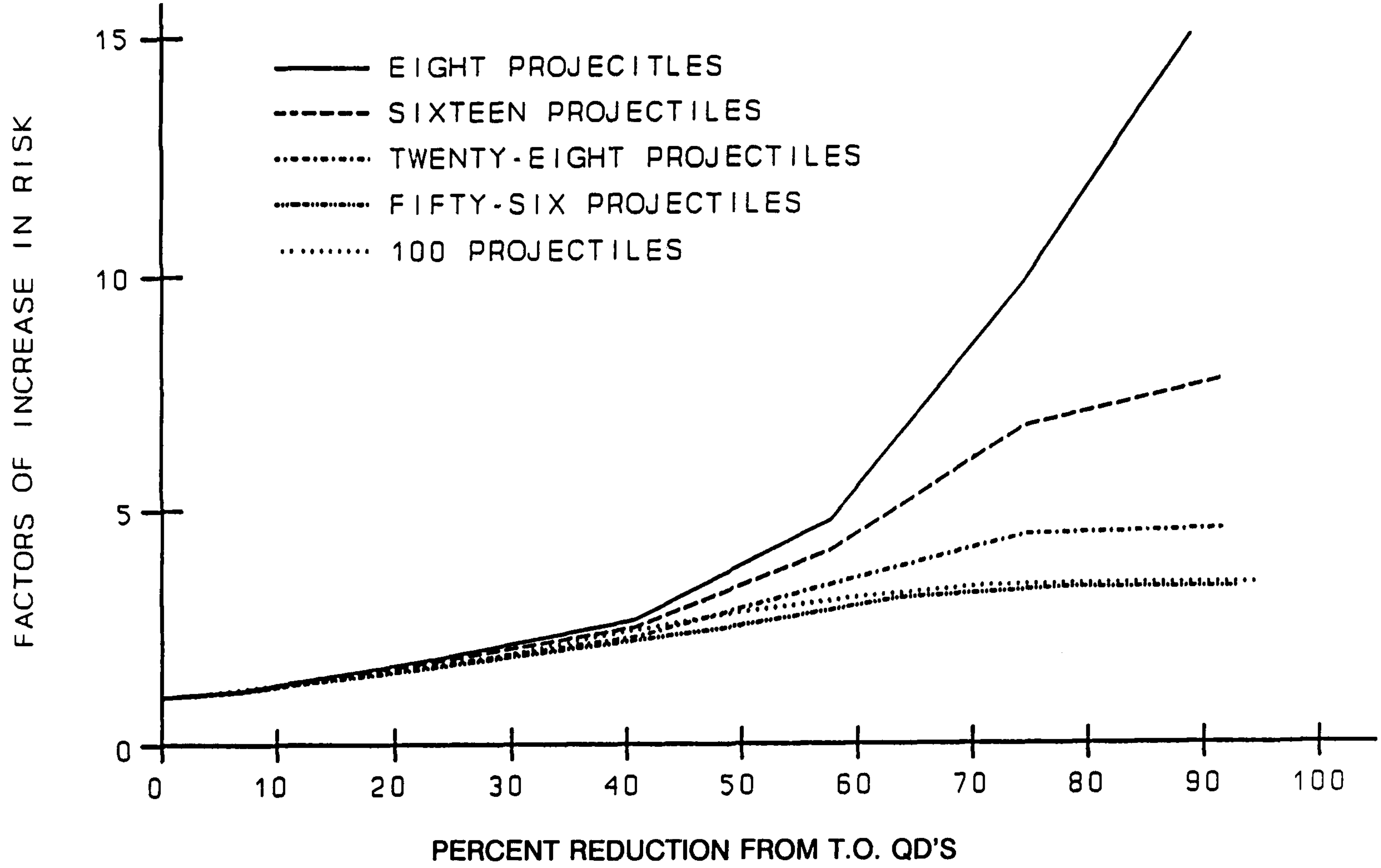

Figure 8. INCREASE IN RISK DUE TO REDUCTION IN THEATER OF OPERATION QD'S (CH. 10 OF STANDARDS)

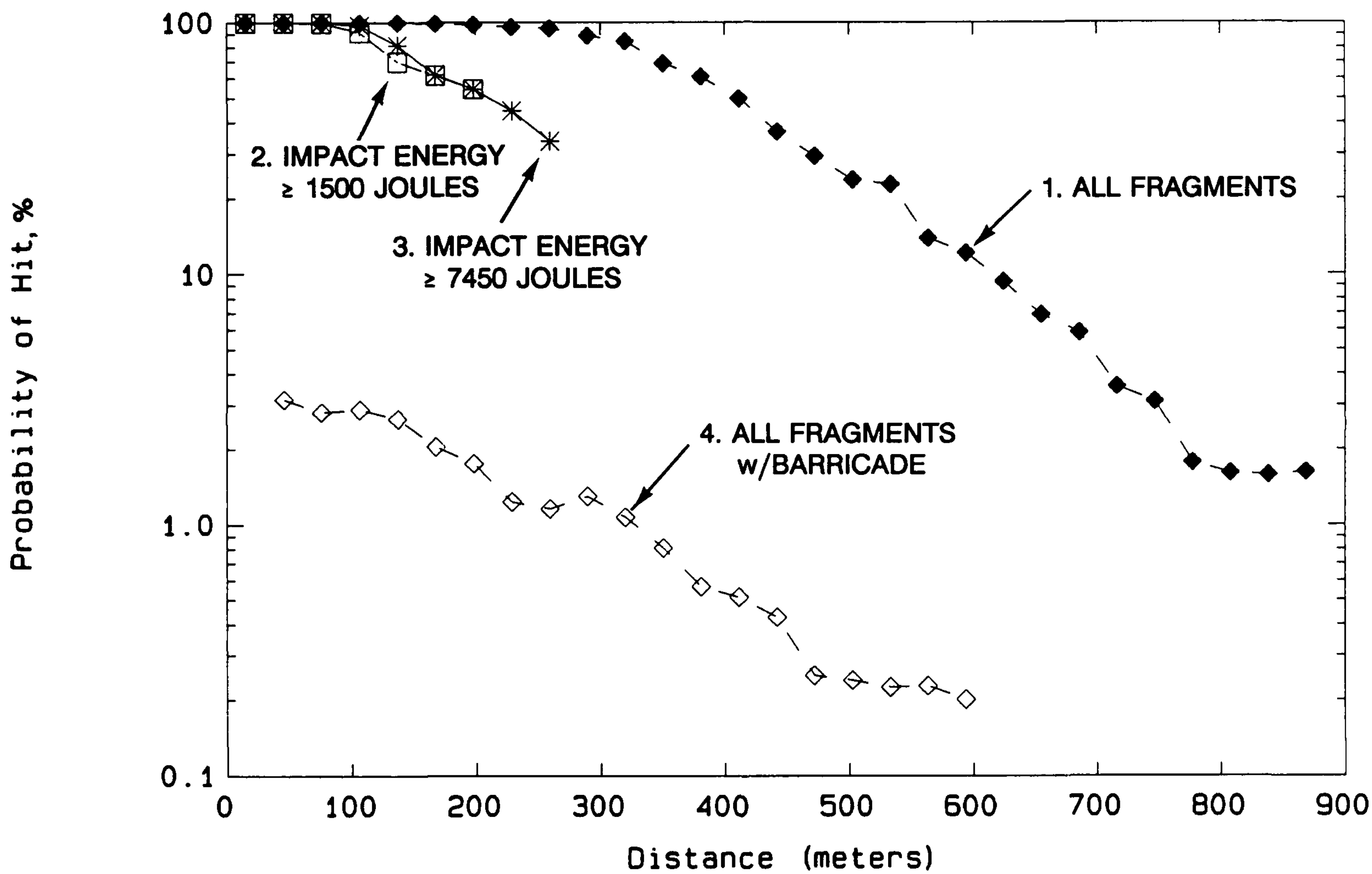

Figure 9. PROBABILITY OF FRAGMENTS HITTING AMMO STACK

TABLE 1.

INCREASE IN RISK DUE TO
Q-D VIOLATIONS FOR OPEN STORAGE
OF AMMO IN T.O.'S

			FACTORS OF INCREASED RISK WITH:	
# PROJECTILES ON FACE	NEW, KG	Q-D,M*	30% QD REDUCTION	50% QD REDUCTION
8	447	180	2.2	3.8
16	894	180	2.0	3.4
28	1565	180	1.9	2.9
56	3192	203	1.9	2.5
100	5588	269	1.9	2.8

* FROM CHAP. 10 OF DD6055.9-STD

THE THREAT RELATED ATTRITION (THREAT) SYSTEM
CASUALTY ESTIMATION FACILITY MODEL

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The U. S. Air Force Human Systems Division, Operational Analysis Systems Division (HSD/YAO) and its contractor, BDM International, Inc., are developing a series of computer simulation models to estimate wartime personnel attrition on airbases. Casualty estimation in structures subjected to the effects of conventional munitions is a key part of this effort. This paper presents the methodology developed to estimate such casualties, and compares model results to historical and recent Gulf War events. While primarily focused on the effects of munitions against personnel in facilities, the underlying approach is felt applicable to a wide variety of problems in which an estimation of the effects of explosives against personnel is required.

A. INTRODUCTION

Casualty attrition rates are used by numerous Air Staff offices to satisfy a variety of planning and programming requirements, including identifying medical manpower and material needs, planning for facilities and equipment, and identifying wartime personnel replacement needs. Because casualty estimates are essential to such wartime planning activities, the Air Force Human Systems Division (HSD/YAO) has undertaken a program to develop a consistent, auditable, and enduring modeling system to perform casualty estimation analysis. Acting as the HSD's prime contractor, BDM International is developing the THREAT (Threat Related Attrition) modeling system. The THREAT system is designed to respond to evolving worldwide threats, improvements in airbase facilities and protection systems, and developments in enemy weapon systems, to provide relevant and up-to-date attrition rate estimates.

The THREAT system is comprised of a number of integrated computer simulation models. At the most fundamental level are the *facility* models, which predict casualties resulting from specific weapons delivered against individual structures. Results from the facility models are then used by higher level models to predict casualties for individual airbases and military theaters of operation.

Because the facility models represent the foundation of the THREAT system, their ability to accurately predict the numbers and types of casualties is key to the overall success of the system. This paper summarizes the methodology developed to accomplish facility modeling for the THREAT system and provides comparisons of model estimates to historical and recent Gulf War events.

B. BACKGROUND

Airbase casualties are generally expected to be the result of air-delivered munitions against personnel in structures. In the past (Ref. 1), analysis of airbase attrition relied heavily on the application of casualty trends observed in the battlefield. Review of the literature shows that the nature and extent of casualties in structures is very much different than those which occur on the battlefield. In general, battlefield casualties are caused primarily by direct weapons effects such as overpressure and fragmentation. On the other hand, casualties in structures are due largely to secondary weapon effects, such as flying and falling debris, and structural collapse. The ratio of fatal to nonfatal casualties in structures is also different from that on the battlefield. The THREAT facility models attempt to account for these differences by pursuing a detailed examination of the forces acting on a structure, the response of the structure to the forces, assessment of interior hazards, and determination of casualties based on the severity of these hazards.

Weapon effects models developed in the past typically have not combined all of these factors. Methods, procedures, and data have been assembled to assess damage to buildings from conventional munitions (Ref. 2-5), however, these often lack the critical links between weapon effects and personnel survivability. A primary objective of this effort was to integrate the information necessary to estimate casualties in structures into a single computer simulation model.

Initial development of the facility models focused on providing a capability to examine the effects of specific bombs versus particular structure types. The first structure types examined include unprotected and select protected facilities. Munition types include conventional general purpose bombs of varying sizes. Development of these models provide a proof-of-concept for the modeling system as a whole and serve as a baseline for future system upgrades.

C. MODEL DESCRIPTION

The facility models are designed to provide detailed assessments of the effects of general purpose bombs delivered against airbase facilities. Currently modeled structural classes include unprotected, NATO semihardened (above ground and buried), and survivable collective protection shelters (SCPS). The response of each structure is very much dependent on its construction. For this reason, each class of structure is modeled separately. A complete treatment of each class is beyond the scope of this paper. To illustrate the methodology in general, the unprotected facility model will be discussed.

Each model has five principal components, including facility and weapon event description, weapon effects, structural response, interior environment assessment, and casualty estimation. A summarized description of each segment is provided below.

1. Facility and Weapon Event Description

To allow assessment of a variety of unprotected structures, structure data files were developed to represent typical unprotected facilities on an airbase. These included unreinforced masonry, reinforced concrete frame, steel frame, and wood frame. The structure data files contain a simplified representation of each structure. Information stored in the data files includes the size of the building; the number of stories; the number of rooms per story; the number and types of walls, floors, ceilings, columns, beams, and windows; and the location, orientation, and interdependencies of the components. For unprotected structures, the data files also contain rules to predict progressive structural collapse following assessment of the primary weapon effects.

The model user initiates execution of the program by selecting the facility type to be analyzed. The user then specifies the weapon, detonation location, and soil type. Weapon choices include 100-, 250-, 500-, 1000-, and 2000-pound general purpose bombs. Soil types include dry loose sand, wet loose sand, dry dense sand, wet dense sand, moist clayey sand, wet silt clay, wet sandy clay, and saturated sandy clay. Direct hits may be analyzed by specifying weapon detonation locations within the structure. The model does not specifically address weapon fuzing, penetration, ricochet, or trajectory (it is left to the analyst to specify realistic weapon detonation locations). Initial populations of each room are also specified by the user.

2. Weapons Effects

The detonation of a weapon, such as a general purpose bomb, produces several effects that may pose a hazard to structures and/or personnel. General purpose bombs are comprised of essentially three components: an outer steel casing, an inner high explosive charge (such as TNT), and a fuze. Fuzes may be set to trigger either above ground, on contact, or at some prescribed time after contact. In general, contact fuzed weapons are used for attacking soft, above-ground targets, and delay fuzed weapons are used for attacking buried or hardened targets.

A contact fuzed weapon detonating on the ground surface will generate shock waves in the air. This is termed airblast and is considered the primary threat to above-ground structures[1]. Airblast pressures in the freefield are termed incident pressures and are typified by an instantaneous rise in pressure followed by an exponential decay. Integration of the area under the pressure-time history is referred to as the blast impulse. Peak incident pressure and impulse are a function of the weapon charge weight and range from the explosion, and are defined in the literature (Ref. 3). The pressure-time history is commonly simplified as a triangular pulse having an instantaneous rise and linear decay. This approximation is represented in the model as follows:

$$P_i(t) = P_0\left(\frac{t - t_0}{t_0}\right) \quad \text{for } t \le t_0 \tag{1}$$
$$= 0 \quad \text{for } t > t_0$$

where:

$P_i(t)$ = positive incident pressure as a function of time
t = reference time
P_0 = peak positive incident pressure (psi)
t_0 = positive phase duration (msec) = $2i_s/P_0$
i_s = positive phase impulse (psi-msec)

As the shock wave strikes an object, the interface pressure acting on the object intensifies based on the angle of incidence between the object and the pressure wave, and the magnitude of the pressure wave. A reflection factor $C_{r\alpha}$ is found from empirically derived relationships available in the literature (Ref. 3). To calculate reflected pressure and impulse, the model determines the distance and reflection angle between the weapon and structural components having line-of-sight to the detonation. The magnitude of the reflected pressure and impulse acting on these components is stored and used later for structural response calculations.

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1 While fragment loading is also a concern, airblast is dominant and its effects are assumed to be the primary indicator of damage. Assumption consistent with the literature (Ref. 2).

Delay fuzed weapons detonating below the ground surface will generate cratering and groundshock. Both these phenomena are strongly dependent on the soil type in which the event takes place. Crater dimensions are calculated in the model based on standard relationships found in the literature (Ref. 3). Groundshock, while a significant threat to buried structures, is not calculated as a threat to above-ground, unprotected structures[2].

Weapons which penetrate and detonate inside a hardened structure generate extreme levels of airblast overpressure due to confinement of the blast by the structure itself. Such confined overpressures are not calculated for detonations inside unprotected structures. The relatively light walls of unprotected structures are assumed not to provide the blast containment necessary to develop such pressures. While it may be true that unprotected structures confine the blast to some degree, analysis of this point was beyond the scope of the model at this time.

3. Structural Response

In general, the response of a structure to airblast forces will be a function of either the pressure, impulse, or a combination of both. Identification of the dominant response mode can be made by examining the duration of the blast load T and the natural period of the structure T_n (Ref. 2):

$$\frac{T}{T_n} \leq 0.3, \qquad \text{response impulse dependent only} \tag{2}$$

$$0.3 < \frac{T}{T_n} < 50, \qquad \text{response pressure and impulse dependent} \tag{3}$$

$$\frac{T}{T_n} \geq 50, \qquad \text{response pressure dependent only} \tag{4}$$

The relatively short duration loads from general purpose bombs of the size included in this study produce duration-to-natural period ratios of less than 0.3 for most structural components (Ref. 2). Exceptions include brittle components such as windows.

The response of the structure as a whole is calculated by assessing the response of individual components. The capacity of components to withstand impulse forces was obtained from the literature (Ref. 2). Data are stored on the reflected impulse required to cause slight, moderate, and total damage for each component. Component types currently available in the model include unreinforced masonry walls (4 to 12 inches); reinforced masonry walls (6 to 12 inches); reinforced concrete walls (4 to 12 inches); light stud/metal walls; light metal, wood, and concrete floor/roof elements; and heavy timber, concrete, and steel beams and columns. Windows are pressure sensitive and the reflected pressure required to cause breakage is stored.

The model initiates assessment of the facility by first determining those components having line-of-sight to the weapon. The reflected impulse and pressure are calculated as described above. Based on the impinging reflected impulse, components are classified as having either total, moderate, slight, or no damage. Should a wall, floor, or ceiling element suffer total damage, the model "opens" the adjoining room to subsequent blast effects. In this way the blast is tracked as it propagates through the facility.

Blast can be attenuated to a significant degree as it propagates through a structure. Review of the literature (Ref. 6) on the effects of 250 kg general purpose bombs against unreinforced masonry dwellings indicates the

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2 Assumption consistent with the literature (Ref. 2)

average radius of full demolition for near-miss events was significantly greater than that for direct hits. The reason is that for direct hits, blast must propagate through more obstructions (walls, ceilings, etc.) than for near misses (where blast may propagate unobstructed over large distances). This attenuation of blast by building components is represented in the facility models.

For buried detonations, damage to unprotected structures is based on the dimensions of the crater with respect to the facility. First floor components within the crater itself are assumed to be totally destroyed. Component damage then decreases with increasing distance. For shallow buried detonations which generate both airblast and cratering, the effects of each are assessed. Damage is determined as the greater of the two effects.

Following assessment of the primary weapon effects, the model assesses progressive structural collapse. As stated earlier, collapse rules are stored in the structure data file. The rules define loadbearing dependencies between components. Should a loadbearing wall on the second story have the first story wall below it destroyed by blast, the second story wall would be noted as unstable, and would be assessed to be collapsed. Currently, the model does not assess collapse from the dynamic loading of upper-level debris falling on lower levels.

4. Interior Environment

After analyzing the structure's response to the weapon, the model assess the relative severity of hazards to personnel in each room. Hazard environments assessed include overpressure, velocity (floor motion) primary fragments (bomb splinters), secondary projectiles (flying debris) and collapse (falling debris). Hazards are rated from each cause as either severe, moderate, light, or none. Each cause is described below.

Fast rising overpressure can injure personnel as the overpressure compression wave propagates through the body and reflects at internal air-tissue interfaces, such as the ears and lungs. Common injuries include ruptured ear drums and lung lesions. The model records the peak incident pressure and duration in each room as the blast propagates through the facility. These values are then compared to overpressure injury relationships described in the next section which relate a person's probability of sustaining a fatal, serious, or slight injury to the magnitude and duration of the overpressure. Based on this assessment, overpressure hazard is rated.

Personnel may be injured from being knocked off their feet and/or otherwise displaced as the floor heaves in response to the blast. This phenomena was designated velocity hazard. Velocity hazard is assessed by noting the state of a room's floor damage. It was assumed that increasing floor damage corresponded to increasing velocity hazard. Based on the final floor damage state, velocity hazard is rated.

Primary fragments are pieces of the weapon casing flying away from the detonation at extremely high velocities (5000 to 7000 fps). Primary fragments are the most significant injury mechanism for weapons detonating in the open against unprotected personnel. However, in structures, the literature indicates that even light partition walls provide surprisingly effective protection (Ref. 9). The severity of the primary fragment hazard is rated in the model based on the distance and number of intervening walls between the weapon and personnel at risk.

Secondary projectiles are created when a wall is breached or spalled by blast, causing numerous pieces of concrete, masonry, and other building materials to fly through the air. The severity of the secondary projectile hazard was rated based on the damage sustained by the walls of a room. It was assumed that increasing wall damage corresponded to increasing secondary projectile hazard. Based on the final damage state of all walls associated with a room, the secondary projectile hazard is rated.

Personnel may also be injured from falling pieces of debris. This phenomena was designated collapse hazard. Collapse hazard is assessed by noting the state of a room's ceiling damage. It was assumed that increasing ceiling damage corresponded to increasing collapse hazard. Based on the final ceiling damage state, collapse hazard is rated.

5. Casualty Estimation

Following assessment of the interior hazards described above, the model estimates the resultant casualties in the structure. To accomplish this, links had to be established between the hazards and the probabilities of personnel sustaining fatal, serious, and slight injuries. Establishing these links was perhaps the most difficult aspect of the study, given the natural variability in expected personnel location and posture, the complexities of estimating human response to trauma, and the inability to precisely define the environment to which personnel would be subjected. However, the literature does provide information from laboratory studies and historical events. Combining these sources allowed provisional relationships to be defined. Research is ongoing to better define these relationships.

Overpressure casualties are estimated based on the magnitude and duration of the incident pressure in a room. The literature (Ref. 10-12) provides information from animal studies extrapolated to estimate human response. The casualty relationships derived from this information was implemented into the models.

Casualties from velocity, primary fragments, secondary projectiles, and collapse were developed from historical events. The literature provided information from the London Blitz which identified actual numbers and causes of casualties at various ranges and levels of structural damage from the listed hazards. This information was used along with engineering judgment to establish the casualty frequencies for the above causes based on their severity.

The method for determining casualties in a room is as follows. Given that the model has determined the probability of personnel incurring a fatal injury from hazard i (denoted $p_{k(i)}$), a fatal or serious injury from hazard i (denoted $(p_{k+s(i)})$, and fatal or serious or slight injury from hazard i (denoted $(p_{k+s+sl(i)})$, and all n hazards have been assessed, the overall probability of incurring a fatal injury P_k in a room is calculated as:

$$P_k = 1 - \prod_{i=1}^{n} [1-p_{k(i)}] \tag{5}$$

the overall probability of incurring a fatal or serious injury P_{k+s} in a room is:

$$P_{k+s} = 1 - \prod_{i=1}^{n} [1-p_{k+s(i)}] \tag{6}$$

and the overall probability of incurring a fatal or serious or slight injury P_{k+s+sl} in a room is:

$$P_{k+s+sl} = 1 - \prod_{i=1}^{n} [1-p_{k+s+sl(i)}] \tag{7}$$

The numbers of fatal N_f, serious N_s, and slight N_{sl} in a room is then found based on the above probabilities and the initial population of the room N_{init} as:

$$N_f = N_{init} (P_k) \tag{8}$$

$$N_s = N_{init} [(P_{k+s}) - P_k] \tag{9}$$

$$N_{sl} = N_{init} [(P_{k+s+sl}) - (P_{k+s})] \tag{10}$$

Fatal, serious, and slight casualties are then summed over all rooms to obtain total estimated casualties in the facility.

D. MODEL VALIDATION

To validate the performance of the model, comparisons were made between model results and historical data. To accomplish this, a typical block of row houses of the size and construction type prevalent in London during World War II was simulated. Two points of comparison were pursued: (1) comparison of modeled to historical results of the degree of structural damage caused by general purpose bombs, and (2) comparison of modeled to historical results of the frequency of fatal, serious, and slight casualties as a function of range from the weapon.

To compare the damage caused by general purpose bombs, information was available in the literature describing the damage suffered by London rowhouses due to German bombs. Using the simulated block of rowhouses, bombs were modeled at over 500 locations in and around the houses. Depth-of-burst estimates were made based on reported crater dimensions from the historical data. Results from all modeled events were tabulated. Comparisons between modeled and historical damage and casualties were favorable, and thus supported use of the models to represent weapons and facility types for which historical data is not available.

Comparisons are now being pursued between modeled and actual causes of casualties at various ranges. Calibration of the models using such historical data provides the best and most realistic estimate of casualties expected from conventional munitions delivered against personnel in unprotected structures.

E. GULF WAR EVENT COMPARISON

The reason for developing the model described above is to provide military planners the capability of estimating casualties in modern structures subjected to modern weapons. The THREAT models were used in a program initiated before the Gulf War to estimate expected numbers of noncombatant casualties in Baghdad, Iraq. Post war surveys have indicated that the THREAT System estimates were quite accurate. Additionally, an event occurred during the war for which the accuracy of the facility model could be checked directly. On February 25, 1991, an Iraqi Scud missile struck an aircraft hangar being used to house U. S. personnel supporting Desert Storm operations. Of the roughly 150 troops in the hangar, 28 were killed and 100 injured[3]. In the aftermath of this event, the facility model described above was exercised to investigate the correlation between the model and the actual event. Because of limited information regarding the exact weapon type, detonation location, structure type, and distribution of personnel in the facility, certain assumptions were made. These assumptions were as follows:

- Of the Scud missiles in the Iraqi inventory, the most probable one used against the U. S. troops was the *Al Hussein*. The *Al Hussein*[4] is a derivative of the Soviet *Scud-B* missile, modified to achieve greater range through additional solid propellant and reduced warhead weight. The warhead is a conventional high explosive blast/fragment type with a total weight of

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3 Figures reported by Cable News Network (CNN), February 26, 1991.

4 Source: Janes Strategic Weapons Systems, 1989.

about 1100 lbs, estimated charge weight of 550 lbs. Characteristics of the warhead were deemed similar to a general purpose bomb of similar weight.

- The structure used to house the troops was a steel framed, metal sided aircraft hangar. The hangar structure currently available in the facility model was used to represent this structure. The modeled hangar has dimensions of 200 by 150 by 30 feet. The shelter is open inside and offers no protection from interior walls.
- Troops were evenly distributed throughout the facility. Protective gear was not in use, and the vulnerability of personnel to weapon effects was essentially similar to the civilian population studied above.
- The Scud missile struck roughly in the center on the hangar and detonated on contact with the ground.

Based on these assumptions, the modeled results were as follows (modeled serious and slight injuries were summed to obtain total injuries):

EVENT	KILLED	INJURED
Actual	28	100
Modeled	20	79

It should be noted that the THREAT models account for casualties resulting from direct and secondary weapons effects (overpressure, fragmentation, falling debris, etc.) but do not account for subsequent casualties due to fire. This may account for the model's underprediction. However, given the inherent uncertainties in any such analysis, the results were viewed as excellent.

F. CONCLUSIONS

The existing facility-level models provide a useful tool for estimating personnel casualties in structures. New weapon and facility types are being added to increase the scope of the models' analysis capabilities. A great deal of work still needs to be completed to fine tune the models, especially in the area of human vulnerability. This is an ongoing research effort, and upgrades to the models are expected to be evolutionary in nature. Continued model development should offer significant opportunities to assess the effectiveness of evolving weapon and protection systems, and allow for effective post attack recovery operation planning. The underlying approach, which relies on a fundamental assessment of weapon effects, structural response, and human vulnerability, is felt applicable to a wide variety of problems in which an estimation of the effects of explosives against personnel is required.

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MR.	STEVENSON	RANDY	NORTHROP CORPORATION
TSgt	STEWART	DANIEL	314 AW/SEW
MR.	STINCIC	THOMAS	SENECA ARMY DEPOT
MR	STRATMAN	GEORGE	OGDEN AIR LOGISTICS CENTER (AFLC)
MS.	STUCKEY	BEVERLY	LONE STAR ARMY AMMUNITION PLANT
MR.	STUDDERT	WILLIAM	U.S. ARMY MATERIEL COMMAND
MR.	SUMMERS	RICHARD	DEFENSE CONTRACT MGMT DISTRICT WEST
MR	SUTHERLAND	JOHN	MARTIN MARIETTA ASTRON. GROUP
MR.	SWANEY	DANIEL	THIOKOL CORPORATION
MR	SWANSON	NORMAN	HURLBURT FIELD
MR.	SWANSON	KEITH	834 AIR BASE WING/SEW
MR.	SWINDALL	TERRELL	U.S. ARMY MISSILE COMMAND
MR	SWISDAK	MIKE	NAVAL SURFACE WARFARE CENTER
GROUP CAPT	SYMONDS	PETER	DEPUTY DIRECTOR
MR.	TALLEY	GARY	THIOKOL CORPORATION
MR.	TANCRETO	JAMES	NAVAL CIVIL ENGINEERING LABORATORY
MR	TATOM	FRANK	ENGINEERING ANALYSIS INC.
MR.	TAYLOR	JOYNER	NEW MEXICO INSTITUTE OF MINING
MR.	TEO	KIAN	CDC CONSTRUCTION & DEVELOPMENT PTE LTD

MR.	THOMAS	JOSEPH	HAWTHORNE ARMY AMMUNITION PLANT
MR.	THOMPSON	JOSEPH	THIOKOL CORPORATION
MR.	THOMPSON	N.	21ST SPACE WING
MR.	THOMPSON	LEROY	U.S. DEPARTMENT OF ENERGY
SFC	THORSON	DONALD	ESCORT & DISPOSAL DETACHMENT
MR.	TIBBITTS	WILLIAM	JET PROPULSION LABORATORY
MR.	TINKLER	WILLIAM	W.S.N. TINKLER
MR.	TOMINACK	JOHN	NAVAL SURFACE WARFARE CENTER
MR.	TOMLIN	MAX	US ARMY STRATEGIC DEFENSE COMMAND
MR.	TORMA	STEVEN	OLIN ORDNANCE
MR	TRIPP	BRIAN	351 MW/SEP
MR.	TSCHRITTER	KEN	SANDIA NATIONAL LABORATORY
MS.	TUCKER	BARBARA	DEFENSE PLANT REPRESENTATIVE OFFICE
MR	TUOKKO	SEPPO	MINISTRY OF DEFENSE
MR.	TWING	CHARLES	U.S. ARMY CORPS OF ENGINEERS
MR.	TWISDALE	LAWRENCE	APPLIED RESEARCH ASSOCIATES, INC.
CAPTAIN	ULSHAFER	MICHAEL	PHILLIPS LABORATORY
MR.	URSERY	ALBERT	DPRO HERCULES
MR.	USKIEVICH	RAY	NAVAL FACILITIES ENGINEERING COMMAND
MR.	VAIDYANATHAN	H.	DEPARTMENT OF NATIONAL DEFENSE
MR.	VAN EVERDINK	LEO	MTMC EUROPE
MR.	VAN EVERY	DESHA	NORTHROP CORPORATION
MR.	VAN RIPER	ED	U.S. ARMY BALLISTIC RESEARCH LABORATORY
MR.	VASELICH	RAYMOND	NASA
MR.	VEZINA	REMI	SNC INDUSTRIAL TECHNOLOGIES, INC.
MR.	VICK	C.	ATLANTIC RESEARCH CORPORATION
MR.	VICKERS	MARVIN	NAVAL SEA SUPPORT CENTER, PACIFIC
MR.	VICTOR	ANDREW	VICTOR TECHNOLOGY
MS.	VINEY	FRAN	DEFENSE CONTRACT MGMT DISTRICT WEST
DR	VRETBLAD	BENGT	FORT F - ROYAL SWEDISH -
MR.	WAGER	PHILLIP	NAVAL CIVIL ENGINERING LABORATORY
MR.	WAGMAN	JAMES	PL/SEW
MR.	WAGNER	WILLIAM	HERCULES INC.
MR.	WALDMAN	BENJAMIN	US ARMY PRODUCTION BASE
CMSGT	WALKER	JOHN	919 SOW/MAEWM

CAPTAIN	WALLACE	DAVID	CHAIRMAN, DOD EXPLOSIVES SAFETY BOARD
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MR.	WALTERS	JAMES	US ARMY NUCLEAR AND CHEMICAL AGENCY
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DR.	WARD	JERRY	DDESB
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MR.	WARWICK	WAYNE	LOCKHEED MSD
MR.	WATANABE	WALLACE	US ARMY CORPS OF ENGINEERS
MR.	WEBSTER	LARRY	DDESB
MR.	WEE	TERRY	CHARTERED INDUSTRIES
MR.	WENDEL	CLIFFORD	AMXRM-SHE
MR.	WHEELER	RONALD	SSI SERVICES, INC.
MR.	WHITE	CHARLES	HQ AFSOC/SEW
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MR.	WILLIAMS	GEORGE	HERCULES, INC.
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MR.	WILLIS	RICHARD	NORTHORP CORPORATION
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MR.	WINGATE	MARK	OLIN CORPORATION
CAPTAIN	WINTLE	FREDERICK	FIELD COMMAND, DEFENSE NUCLEAR AGENCY
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MR.	WITIAK	R.	DCMDS-GBQS
MR.	WOFFORD	KENT	SIERRA ARMY DEPOT
MR.	WOLFGANG	GARY	OLIN ORDNANCE
MR.	WOOD	RANDALL	EG&G MOUND APPLIED TECHNOLOGIES
MR.	WOOD	SCOTT	NAVAL WEAPONS STATION - SEAL BEACH
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CAPTAIN	WORKMAN	RICKEY	HQ USAF WPNS & TACTICAL CENTER
MR.	WU	DA-LIH	BECHTEL NATIONAL
MR.	WYLIE	ALISTAIR	AUSTRALIAN DEFENCE INDUSTRIES, LTD.
LT COL	WYSOWSKI	JOHN	HQ, AIR COMBAT COMMAND
MR.	YAN HAM	NICK	TNO - DEFENSIEONDERZOEK
MR.	YONKMAN	THOMAS	
MR.	YOUNG	MARVIN	GENCORP AEROJET

MR.	YUHAS	JOHN	TECHNICAL ORDNANCE, INC.
MR.	YUN	CHAD	DEFENSE CONTRACT MGMT DISTRICT WEST
MR.	YUTMEYER	WILLIAM	AMC FIELD SAFETY ACTIVITY
COL	ZAKRZEWSKI	STEPHEN	
MR.	ZAUGG	MARK	TOOELE ARMY DEPOT
MR.	ZEHRT	W.	U.S. ARMY ENGINEERING DIVISION
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